RESEARCH TECHNICAL COMPLETION REPORT

PROJECT B-009-IDA

SIMULATION MODEL FOR EVALUATION OF INTERCEPTION LOSS FROM FOREST TREES

PART I: Modeling Snow Interception on Conifers
by Dr. G.H. Belt
of Forestry

PART II: Laboratory Modeling of Snow Interception on Trees
by Dr. Myron Molnau
of Agricultural Engineering

Water Resources Research Institute
University of Idaho
Moscow, Idaho

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16. Abstract This portion of the study was conducted to develop models or methods of defining interception storage of snow on conifer trees. Field data obtained in physical modeling of individual trees and data taken from the literature were used to define mathematical relationships for the intercepted precipitation and modeled "species" variations in trees. The defined relationships were subsequently incorporated in a computer simulation model for prediction of interception storage by a stand of trees.

Comparison of interception storage derived from the stand model with measurements on the model trees indicates reasonable predictive capacity for both individual tree and stand models. Several forms of the sigmoid curve were useful in defining relationships between precipitation, interception storage and the end of storms and vegetational parameters. Surface ratio, related to crown projection area, was found to be a suitable parameter in defining differences in the format of the sigmoid curves.

Second portion of the study was conducted to determine the interception characteristics of both artificial and real trees using artificial snow. A drum apparatus was constructed to allow artificial snow to be dropped over the trees. It was found that for 3 ft. high artificial trees, the smaller branch angles intercept more snow than larger branch angles in terms of interception over projected areas of the tree. The shape of the interception vs precipitation curve is the same for both real and artificial trees except that the amounts are considerably less for real trees. There was no appreciable difference between the interception-precipitation curve for the two heights (3 ft & 6 ft) of the species of trees (real) tested.

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September 1968 - June 1973

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Submitted to

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Water Resources Research Institute
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Moscow, Idaho
C. C. Warnick, Director

FOREWORD

The Water Resources Research Institute has provided the administrative coordination for this study and organized the interdiciplinary team that conducted the investigation. It is the Institute policy to make available the results of significant water related research conducted in Idaho's universities and colleges. The Institute neither endorses nor rejects the findings of the authors. It does recommend careful consideration of the accumulated facts by those who are assuredly going to continue to investigate this important field.

ABSTRACT

This portion of the study was conducted to develop models or methods of defining interception storage of snow on conifer trees. Field data obtained in physical modeling of individual trees and data taken from the literature were used to define mathematical relationships for the intercepted precipitation and modeled "species" variations in trees. The defined relationships were subsequently incorporated in a computer simulation model for prediction of interception storage by a stand of trees.

Comparison of interception storage derived from the stand model with measurements on the model trees indicates reasonable predictive capacity for both individual tree and stand models. Several forms of the sigmoid curve were useful in defining relationships between precipitation, interception storage and the end of storms and vegetational parameters. Surface ratio, related to crown projection area, was found to be a suitable parameter in defining differences in the format of the sigmoid curves.

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TABLE OF CONTENTS

CHAPTER	PAGE
INTRODUCTION	1
PREVIOUS WORK	3
METHODS AND RESULTS	10
The Single Tree Model	14
Interception Storage on Artificial Trees	19
Artificial "Pine" Tree Data	20
Slat Tree Data	23
Interception Storage on Natural Trees	26
Stand Interception Model	32
Examination of the Stand Model	34
CONCLUSIONS	38
REFERENCES	39
APPENDIX	40

PART II

INTRODUCTION AND PURPOSE	46
PAST WORK	47
METHODOLOGY	49
A. Snow Tests	49
B. Experimental Equipment	51

TABLE OF CONTENTS (cont.)

CHAPTER PAGE

1. Snowfall Apparatus 52

2. Trees 54

RESULTS AND DISCUSSION. 57

A. Interception on Artificial Trees. 57

B. Interception on Real Trees and Comparison with Artificial Trees 61

C. Tests on Individual Branches 62

CONCLUSIONS AND RECOMMENDATIONS 65

REFERENCES. 67

APPENDIX: ILLUSTRATIONS 68

PART I

LIST OF TABLES

TABLE		PAGE
Table 1.	Interception by Artificial "Slat Trees During 1970 . . .	12
Table 2.	Interception by "Pine" Trees During 1970	13
Table 3.	Summary of Regression Statistics and Parameters for Artificial Tree Data	21
Table 4.	Summary of Regression Statistics and Parameters for Real Trees Using Sigmoid Interception Curve	31
Table 5.	Prediction of Interception by Using ψ(P) and Stand Model	36

LIST OF TABLES (APPENDIX)

TABLE		PAGE
Table 1.	Snow Interception by Pruned and Thinned Japanese cedar	41
Table 2.	1967 Snow Interception Storage, I_s, Priest River Experimental Forest.	42
Table 3.	Snow Interception by Different Aged Japanese cedar . .	43
Table 4.	Snow Interception by Two Varieties of Japanese cedar .	44

PART I

LIST OF ILLUSTRATIONS

FIGURE | PAGE

Figure 1. Growth curves derived from equation 5 for selected values of the constant "a". 17

Figure 2. Growth curves for equation 7, given selected values of constant "a" when P_o = 0 18

Figure 3. Interception by artificial "pine" trees with different surface ratio, computed using equation 17 22

Figure 4. Interception by artificial "pine" trees, with different surface ratio, computed using equation 18. 24

Figure 5. Interception by slat trees computed using equation 18. . 25

Figure 6. Changes in S and the ratio k/SR as related to SR for artificial tree data 27

Figure 7. Sigmoid Interception curves for two varities of Japanese Cedar: Bokasugi and Kumasugi. 29

Figure 8. Sigmoid Interception curves for Douglas fir and White pine 30

PART II

LIST OF TABLES

TABLE PAGE

Table 1. Size distribution of shredded polyethelene snow 52

Table 2. Variation of snowfall intensity with time. 53

Table 3. Summary of tree types used for interception tests. . . . 56

Table 4. Characteristics of branches used in branch interception tests 63

PART II

LIST OF ILLUSTRATIONS

FIGURE PAGE

Figure 1. Original snowfall apparatus and vibrating platform. . . 71

Figure 2. Artificial tree with soap flake snow. 72

Figure 3. Polyethelene snow on artificial tree. 72

Figure 4. Basic snowfall apparatus. 73

Figure 5. View of drums partially filled with polyethelene snow . 73

Figure 6. Closeup of drum and drive for snowfall apparatus . . . 74

Figure 7. Branch angles and shapes for artificial Canada pine . . 74

Figure 8. Interception on an artificial tree with 30 degree branch angle 75

Figure 9. Test of reproductivity of interception using two 60 degree trees 76

Figure 10. Interception of an artificial tree with a 90 degree branch angle 77

Figure 11. Interception on two similar 90 degree trees 78

Figure 12. Comparison of interception on two trees with 30 and 90 degree branch angles. Test 1. 79

Figure 13. Comparison of interception on two trees with 30 and 90 degree branch angles. Test 2 80

Figure 14. Comparison of interception on two trees with 60 and 90 degree branch angles 81

Figure 15. Interception on artificial Christmas tree (Canada pine) 82

Figure 16. Composite of branch angle tests. 83

Figure 17. Effect of projected area on interception. 84

LIST OF ILLUSTRATIONS (cont.)

FIGURE		PAGE
Figure 18.	Interception tests on entire tree	85
Figure 19.	Interception tests using tops of trees	86
Figure 20.	Interception on concolor fir	87
Figure 21.	Interception on ponderosa pine	88
Figure 22.	Interception on Douglas fir	89
Figure 23.	Interception on grand fir	90
Figure 24.	Interception on individual branches	91

INTRODUCTION

Predicting snow interception by conifers can be viewed as a two faceted problem: first predicting the accumulation of intercepted snow deposited on the tree, and secondly subdividing the accumulated snow into that actually lost through evaporation and sublimation, the net interception loss, and that transported to the ground through melt and mass deposition. The purpose of this study is to develop models of interception storage, I_s, by conifers so that the first facet, the accumulation of snow, can be defined. No attempt is made to deal with the second facet of the problem.

Of particular interest are (1) the mathematical form of the interception-precipitation function which describes net interception on an individual tree at the end of the storm and (2) variations in the interception function or model which are caused by differences in physical characteristics of the tree, and (3) validation of a simple interception model for stands of trees, based on experimentally derived interception models for single trees.

Several models and experimental methods were considered, including digital computer simulation, intensive field measurements of climatic variables influencing rates of interception and evaporation as well as physical modeling. Initial attempts with the first two approaches were frustrated by a number of personnel, logistical and theoretical problems. Consequently, the scope of research effort was narrowed to physical modeling which was conducted in two phases. The first phase was conducted at the Priest River Experimental Forest in northern Idaho under semi-controlled field conditions. The basic approach was measurement of real snow intercepted by artificial trees having well defined physical characteristics. Phase I was directed by Dr. George Belt with cooperation from personnel from the Forestry Sciences Laboratory, Intermountain Forest and Range Experiment Station, USDA Forest Service, Moscow, Idaho. Phase II was conducted in laboratories at the University of Idaho under controlled conditions, utilizing artificial trees and plastic snow applied by a "snow" machine. This work, under the direction of Dr. Myron Molnau of the Agricultural Engineering Department at the University of Idaho, is described in Part II of this report.

PREVIOUS WORK

Review of the literature on interception (Zinke, in Sopper and Lull, 1967; Miller, 1964, 1966) suggests that while a great many studies exist relative to gross interception by different types of vegetation, the process itself is not well understood, particularly in relation to physical characteristics of the vegetation. This is the result of the fact that (a) most studies have been designed in terms of a water balance where interception is determined as a calculated residual as shown in equation 1,

$$\text{Precipitation} - \text{throughfall} = \text{Gross Interception}, \qquad (1)$$

rather than as a direct measurement, and (b) few researchers have attempted to analyze interception in terms of the character of the vegetation.

Merriam (1960) summarizing data in the literature and reworking an earlier equation of Linsley, et al., (1949) expressed interception and subsequent loss by evaporation in an equation of the form:

$$L = S\,(1 - e^{-P/S}) + RET \qquad (2)$$

Where:

L is net interception loss in inches

S is maximum storage capacity of the vegetation in inches

P is storm precipitation in inches

R is surface ratio, of total surface area to crown projection area

E is evaporation rate in inches/hour

T is storm duration in hours

Gross interception, I_S, can be defined from equation 2 as:

$$I_S = (1-e^{-P/S}) \quad (3)$$

Further conceptual development of the interception equation or model is found in the works of several Russian, Japanese and American researchers (Khil'Mi, 1957; Watanabe and Ozeki, 1964; Government Forest Experiment Station (Japan) 1952; Satterlund and Haupt, 1967; and Molnau as reported in Part II). The Japanese research (available only in partial translations) is reported in a sequence of Reports I, Government Forest Experiment Station (Japan) 1952, and II (Watanabe and Ozeki, 1964) from the Japanese Government Forest Experiment Station. These publications deal respectively with 1) a series of phyical modeling experiments which illustrate the significance of specific tree characteristics to the interception process and 2) measurement of interception on Japanese cedar (Cryptomeria japonica) and thinning and pruning treatments designed to reduce the volume of snow interception, "snow crown", to eliminate stem breakage.

The physical modeling experiments described in Report I (Nezui), utilizing wooden tree-like forms, define a number of non-linear relationships between surface area, spatial distribution of surface area, and interception. Most of these descriptive equations also incorporate wind speed as a factor. To generalize, the data suggested that (1) the greater the projected surface area, the greater the depth (and mass) of the intercepted snow. However, for snow accumulation on sloped surfaces, interception was less dependent on projected area and more closely related to the product of the sine of the angle of inclination and interception which occurred on a flat surface of equal size, (2) where surfaces were piled one above another to simulate whorls of branches, interception increased with the 2/5 power of the distance between boards (whorls), and (3) where wood latice structures were used to simulate complex leaf patterns, interception increased with the 1/5 power of the distance between lattice components.

The second report describes experiments done with Japanese cedar to reduce its susceptibility to snow breakage. Through reduction of surface area by pruning, total interception was reduced 30 to 40 percent in comparison with untreated trees. The results of these studies based on approximately 10 storms are in general supported by the earlier modeling studies.

Molnau, also using a modeling approach, employed artificial snow (shredded polyethylene) to examine the interception process in a series of laboratory experiments. Using artificial pine trees, the same as (a) the trees used in the field but also (b) identical and uniform except in branch angle, he was able to show that total interception storage increased as the branch angle (measured from the vertical) decreased and the projected crown area decreased. Artificial-snow interception curves obtained for four conifer species were of the form suggested by Merriam (equation 3).

Satterlund and Haupt, 1967, studied the process of snow accumulation during the storm rather than the end result or "snow crown" of the Japanese workers. Using Douglas fir (Pseudotsuga menziesii var. glauca) and western white pine (Pinus monticola, Dougl.) of sapling size they suggested that the accumulation of intercepted snow as a function of accumulated snow fall could be expressed in terms of a sigmoid or logistic curve as shown below:

$$I_s = \frac{S}{1 + e^{-k(P-P_o)}} \qquad (4)$$

where:

I_s = intercepted snow in inches

S = maximum storage capacity in inches

P = precipitation in inches

P_o = precipitation at the point of inflection of the sigmoid curve in inches

k = an experimentally determined constant.

Khil'mi's (1957) theoretical discussion of rainfall interception provides a valuable conceptual framework for snow interception on both individual and stands of trees. For the individual tree, interception, as a function of precipitation and tree storage capacity, is given by:

$$I_s = \psi (P, r, \mu, h) \tag{5}$$

where:

r = canopy radius (in.)

μ = interception stored per unit volume of canopy (in in./in.^{3})

h = height of tree canopy expressed in terms, r (in.)

The parameters r, μ, h define storage volume in relation to canopy dimensions and are considered independent of P. Hence r, μ, h once defined for a given species, permit I_s to be written as a function of P, ψ (P), only.

The stand model is given in terms of throughfall, F(P) as:

$$F(P) = \left[(1 - \sum_{i=1}^{n} A_i)\, P + \sum_{i=1}^{n} F_i\,(P) \right] \qquad (6)$$

where:

$$F_i\,(P) = \begin{cases} A_i \int_0^{Q_i} \psi_i\,(P)dP & \text{for } P \leq Q_i \\ P - Q_i & \text{for } P > Q_i \end{cases} \qquad (7)$$

F(P) is defined as throughfall in area 1 - A_i where A_i is crown projection area as a proportion of stand area. Q_i is gross precipitation required to saturate the canopy in inches. A_t is total area of the stand; I_i is interception storage on vegetation class i (in.). Equations 6 and 7 can be rewritten in terms of total stand interception, I_t as:

$$I_t = \sum_{i=1}^{n} I_i\,(P) \qquad (8)$$

$$I_i = A_i A_t \int_0^{Q_i} \psi(P)dP \quad \text{for } P \leq Q_i \qquad (9)$$

$$I_i = 0 \quad \text{for } P > Q_i \qquad (9a)$$

These studies suggest that (1) experiments with model trees which are not constructed under assumptions of similitude can provide conceptual if not quantitative information relative to the interception process and (2) snow interception can be described in terms of functional relationships where experimental constants reflect differences in physical characteristics of the tree and/or storms, (3) the creditable results obtained in these studies were, in part, the result of normalization of data. In the Japanese studies the data was normalized in terms of a control surface, or a control tree; in the case of the American study, a double-mass procedure was utilized plotting accumulated interception against accumulated precipitation. Finally (4), the interception functions of Khil'mi (1957) suggests that definition of the individual tree curve of ψ (P) can be used to define total stand interception as the weighted sum of the individual interception curves.

METHODS AND RESULTS

Two sources of data were used: namely results available in the literature and field data obtained specifically for this study.

In field experiments, two types of artificial trees were exposed to snow in a sheltered opening on the Priest River Experimental Forest during the winters of 1969 and 1970. Artificial trees were used rather than natural vegetation because of the natural variation in physical characteristics which occur from tree to tree and the large sample of real trees required to reduce this variation in terms of statistical analysis. Manufactured, artificial trees, lacking in natural variation (and beauty) consequently provided necessary control for experimental purposes.

Two types of artificial trees were used. Twelve artificial pine trees manufactured as "scotch pine" with 30, 14-inch brush-like branches and standing three feet in height were used to determine the influence of branch angle on interception. The branches were wired into position to maintain constant branch angle and crown projection. The influence of surface area was examined using 8 slat trees. These shop-built trees consisted of galvanized metal branches bolted at right angles to a 3-foot threaded-rod "trunk". The branches which were inflexible and rectangular in shape were arranged about the trunk so that as much surface area as possible was exposed to the eye when the tree was viewed from the top. The crown projection area of the "slat" trees was 8269 cm^2 and that of the "scotch pine" trees, 1972, 2667, and 3878 cm^2 respectively for the 30, 60 and 90 degree trees (branch angles were measured from the vertical).

Exposure of the trees was arranged to minimize extraneous influences on the experiment. The measurement site at the Priest River Experimental Forest was situated in a small 100-foot diameter opening the 30-foot trees surrounding. The opening was in a sheltered valley and subject to minimal wind disturbance. As a result of this shelter, snow fell vertically and uniformally on the exposed trees, even during intense storms.

The trees were fixed solidly to wooden platforms and arranged in a rectangular grid pattern simulating a stand of trees. After each storm, the trees were moved to a new position within the grid to permit bias due to storm direction. These precautions minimized variation and permitted examination of the statistical significance of treatment effects.

Table 1

INTERCEPTION BY ARTIFICIAL "SLAT" TREES DURING 1970

Month	1	1	1	1	1	1	2	2	3	3
Day	8	12	16	23	28	31	6	8	1	2
P (in.)	.70	.45	1.16	2.39	.72	.20	.51	.20	.32	.20
Snow density	.12	.10	.10	.16	.11	.11	.09	.07	.05	.07
470*	.177	.193	.291	.259	.196	.055	.287	.028	.130	.079
	.185	.197	.425	.346	.192	.055	.297	.028	.126	.079
940*	.240	.224	.464	.551	.228	.067	.374	.012	.153	.087
	.252	.228	.457	.338	.224	.067	.354	.035	.150	.094
1410*	.268	.251	.551	.212	.240	.083	.406	.031	.181	.114
	.291	.224	.496	.228	.236	.074	.401	.024	.118	.106
1880*	.362	.323	.740	.244	.295	.098	.531	.059	.236	.130
	.385	.307	.874	.165	.283	.114	.520	.063	.236	.166

* Total Surface Area (in^2)

Table 2

INTERCEPTION BY "PINE" TREES
DURING 1970

Month	12	1	1	1	1	2	2	3	3
Day	22	12	16	23	28	2	6	1	2
P (in.)	.65	.40	1.16	2.39	.72	.13	.51	.32	.20
Snow density	.13	.09	.10	.16	.11	.07	.09	.05	.07
	.336	.240	.421	.751	.358	.084	.507	.188	.108
30*	.349	.266	.462	.581	.353	.093	.599	.482	.114
	.337	.256	.495	.600	.401	.087	.483	.238	.105
	.329	.238	.421	.380	.386	.096	.545	.216	.124
	.458	.334	.451	.340	.379	.128	.686	.251	.159
60*	.470	.349	.520	.976	.422	.123	.747	.284	.181
	.324	.238	.344	.402	.324	.086	.497	.204	.117
	.357	.276	.528	.373	.340	.098	.621	.142	.142
	.366	.279	.550	.341	.357	.108	.601	.213	.156
90*	.333	.265	.417	.421	.341	.097	.534	.250	.156
	.310	.245	.484	.230	.276	.094	.471	.213	.137
	.345	.271	.503	.434	.334	.109	.541	.242	.166

* Branch Angle (degrees from vertical)

Measurement of intercepted snow was made by weight. At the end of each measuring period the artificial tree and intercepted snow were placed in a plastic bag in a warm location so that the captured snow would melt into the bag for subsequent weighing. Intercepted snow on the slat trees was determined by physically weighing the tree and snow using a portable frame and scale. The slat trees were too heavy to be handled in the same manner as the artificial "pine" trees. Except for storms when snow "capped" the top of the tree and subsequently fell before measurement, the weighing procedure described here proved adequate. Using these methods interception data were obtained from 4 storms in 1969 and 12 storms in 1970. The subsequent discussion is based on 9 storms, that occurred in 1970, where measurement error and missing data were minimal. Data from these storms, summarized in Tables 1 and 2, were converted to areal inches (from weight) based upon crown projection area for analysis.

The Single Tree Model

Intuitively, and from experimental evidence previously presented, the growth function expressing interception must be of the sigmoid type. The initial increase in interception rate would seem to result from the bridging effect of snow forming additional surface area or the increasing overall cohesiveness of the snow laden branch. The final decrease in rate is almost certainly a result of reduction in storage capacity of the tree. From the work of Nezu, et al. (1957) with Japanese cedar, it is obvious also that loading of snow can cause increases of decreases in surface area (depending on branching habit) by alteration of the branch angles. Further, such changes could occur at various times during the interception period and result in either increases or decreases in the interception rate, as well as total storage capacity. Considering the aforementioned potential for variation due to snow density, cohesiveness, etc., it would seem reasonable to expect departure from the symmetric sigmoid curve suggested by Satterlund and Haupt (1967) and expressed in equation 4. A more general form of equation 4 can be written as:

$$I_S = \frac{S}{a + e^{-k(P-P_o)}} \qquad (10)$$

where "a" is a variable rather than a constant equal to 1.0. Assuming $P = P_o$, equation 10 reduces to:

$$I_S = \frac{S}{a + 1} \qquad (11)$$

Then the inflection point occurs between:

$0 < I_S < S/2$ if $a > 1$

$I_S = S/2$ if $a = 1$

$S/2 < I_S < S$ if $0 < a < 1$

$S < I_S < \infty$ if $-1 < a < 0$

The effect of change in the magnitude of "a" on the position of the inflection point can be seen in Figure 1. Another variation in the sigmoid curve is recognized when $P_o = 0$ and equation 10 becomes:

$$I_s = \frac{S}{a + e^{-kP}} \tag{12}$$

With this form, the inflection point occurs at the same position on the vertical scale according to equation 11; however, the horizontal scale is shifted so that the inflection point occurs at $P = P_o = 0$. These forms of the sigmoid curve are generalized in Figure 2 for $P_o = 0$. It should be noted that for equations 10 and 12 respectively, that when $P = 0$:

$$I_s = \frac{S}{a + e^{kP_o}} \neq 0 \tag{13}$$

and

$$I_s = \frac{S}{a + 1} \neq 0 \tag{14}$$

This suggests that to meet the physical requirement $I_s = 0$ when $P = 0$, a correction factor must be employed so that equations 10 and 12 become:

$$I_s = \frac{S}{a + e^{-k(P-P_o)}} - \frac{S}{a + e^{kP_o}} \tag{15}$$

$$I_s = \frac{S}{a + e^{-kP}} - \frac{S}{a + 1} \tag{16}$$

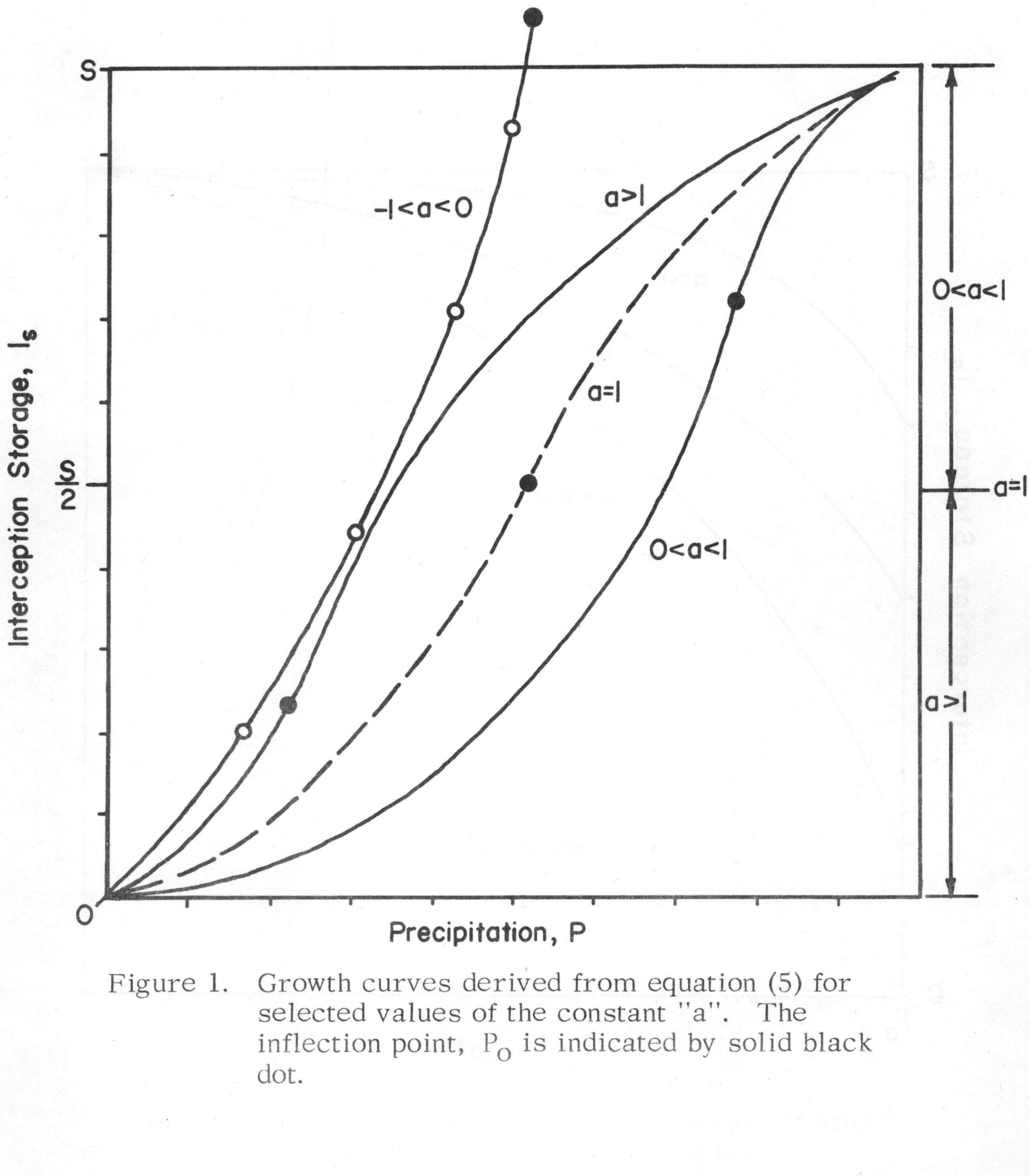

Figure 1. Growth curves derived from equation (5) for selected values of the constant "a". The inflection point, P_O is indicated by solid black dot.

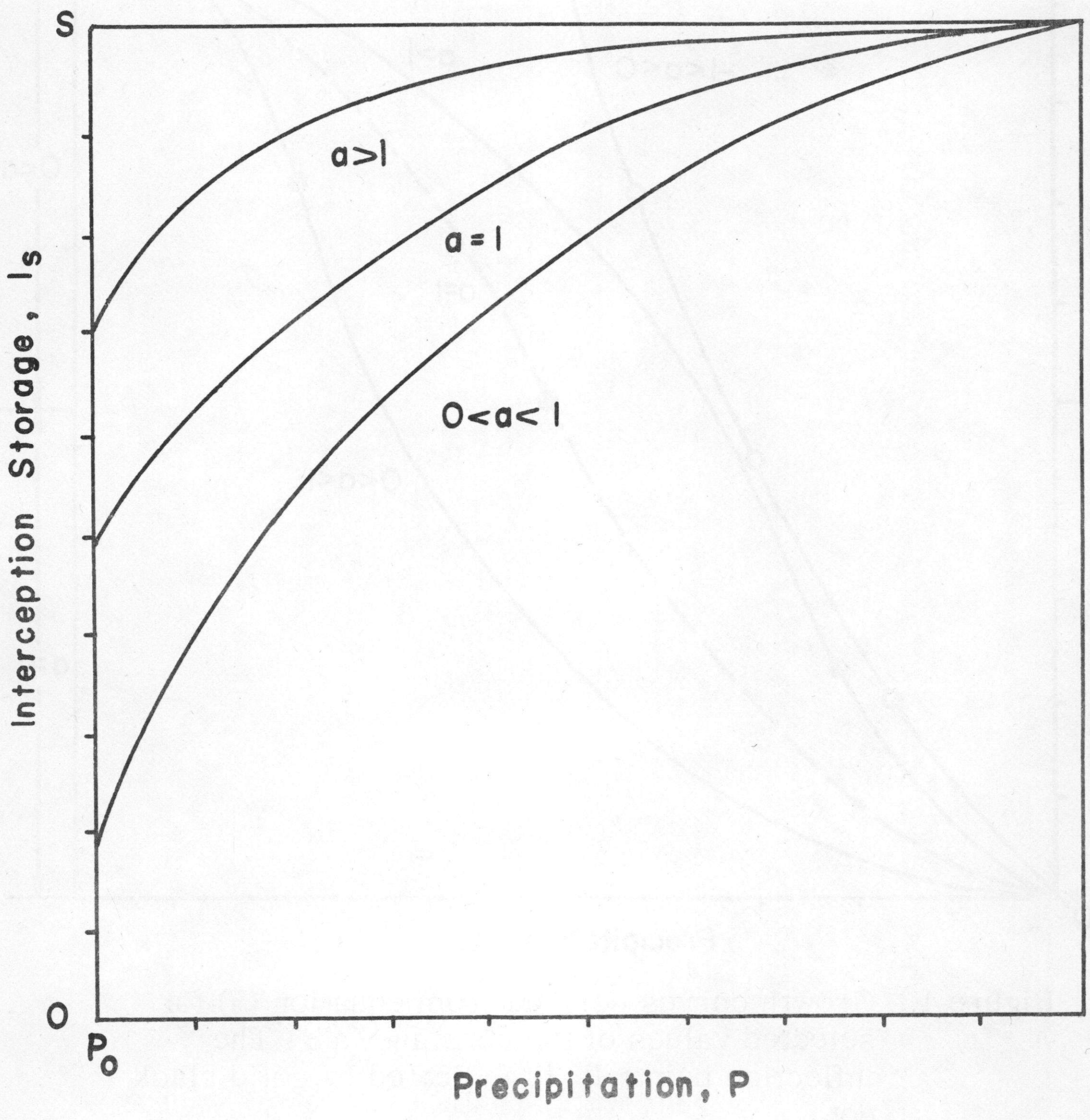

Figure 2. Growth curves for equation 7, given selected values of constant "a" when $P_o = 0$.

Graphically, the correction factor can be viewed as a displacement on the vertical axis where I_s is plotted as a function of P. Numerically the significance of the correction factor in equation 16 depends on the magnitude of the product kP, and in equation 15 on the product kP_o.

Finally it should be noted that equation 16 provides a growth curve similar in shape to that suggested by Merriam (1960) in equation 3 and that equations 3, 15 and 16 provide possible definitions for Khil'mi's (1957) interception function $\psi(Q)$.

Interception Storage on Artificial Trees

Using data in Tables 1 and 2, a computer was used to obtain least square fits to the linear forms of equations 3 and 4, given below.

Equation 3 can be written as:

$$\ln\left[1 - \frac{I_s}{S}\right] = (-P/S)k + c \qquad (17)$$

or

$$Y = (x)b + c$$

and similarly equation 4 becomes:

$$\ln\left[\frac{S}{I_s} - a\right] = -kP + c \qquad (18)$$

or

$$Y = (x)b + c$$

where for a perfect fit c = 0, and k = 1. In both equations 17 and 18, S must be estimated using graphical procedures. Several regressions were necessary for each data set with different estimates of S to obtain a "best" fit as determined by the linear correlation coefficient, r. The correction factors were ignored in the fitting procedure since doing so had no effect on the estimates of k and P_o. In both equations 15 and 16, the constant, "a", was assumed equal to one as a first approximation. This and the other approximate procedures described above were deemed sufficient, since the least square procedure optimized the regression in terms of the natural log transforms rather than the untransformed raw data, in itself only an approximation.

To describe differences in total surface area or "leaf" area of the artificial trees, a surface ratio term was defined. The total projected surface area of the slats or "needled" branches, divided by the crown projection area, yielded the surface ratio, SR.

Artificial "Pine" Tree Data

In Table 3 are summarized the regression parameters obtained using data from Table 2 for trees having branch angles of 30, 60 and 90 degrees and corresponding surface ratios of 1.37, 1.01 and .70. It is clear from the greater r values and smaller error of estimates, $S_{y.x}$, that equation 17 provides the better fit. The fitted curves are shown in Figure 3. Note that as the surface ratio increases, and the

Table 3

SUMMARY OF REGRESSION STATISTICS AND PARAMETERS
FOR ARTIFICIAL TREE DATA

Artificial Tree	Branch Angle	Surface Ratio	Regression Equation 1/	S (in)	k	C	P_o (in)	r	$S_{y.x}$
"Pine"	30°	1.37	17	.59	.94	.10	--	.89	.53
			18	.59	2.23	--	.48	.87	.85
	60°	1.01	17	.55	.65	.24	--	.97	.17
			18	.55	1.75	--	.49	.92	.50
	90°	.70	17	.36	1.46	.28	--	.97	.21
			18	.36	5.89	--	.26	.98	.26
Slat	90°	1.47	17	.51	.04	-.56	--	.15	.37
			18	.51	5.35	--	.43	.95	.57
		1.10	17	.51	.03	-.57	--	.11	.38
			18	.51	7.65	--	.42	.99	.29
		.74	17	.39	.81	.05	--	.54	.66
			18	.39	6.68	--	.44	.99	.36
		.37	17	.30	.72	.02	--	.46	.94
			18	.30	6.00	--	.47	.99	.22

1/ Equation (17) $\ln\left(1 - \frac{I_s}{S}\right) = (-P/S)k + c.$

(18) $\ln\left(\frac{S}{I_s} - 1\right) = -kP + kP_o.$

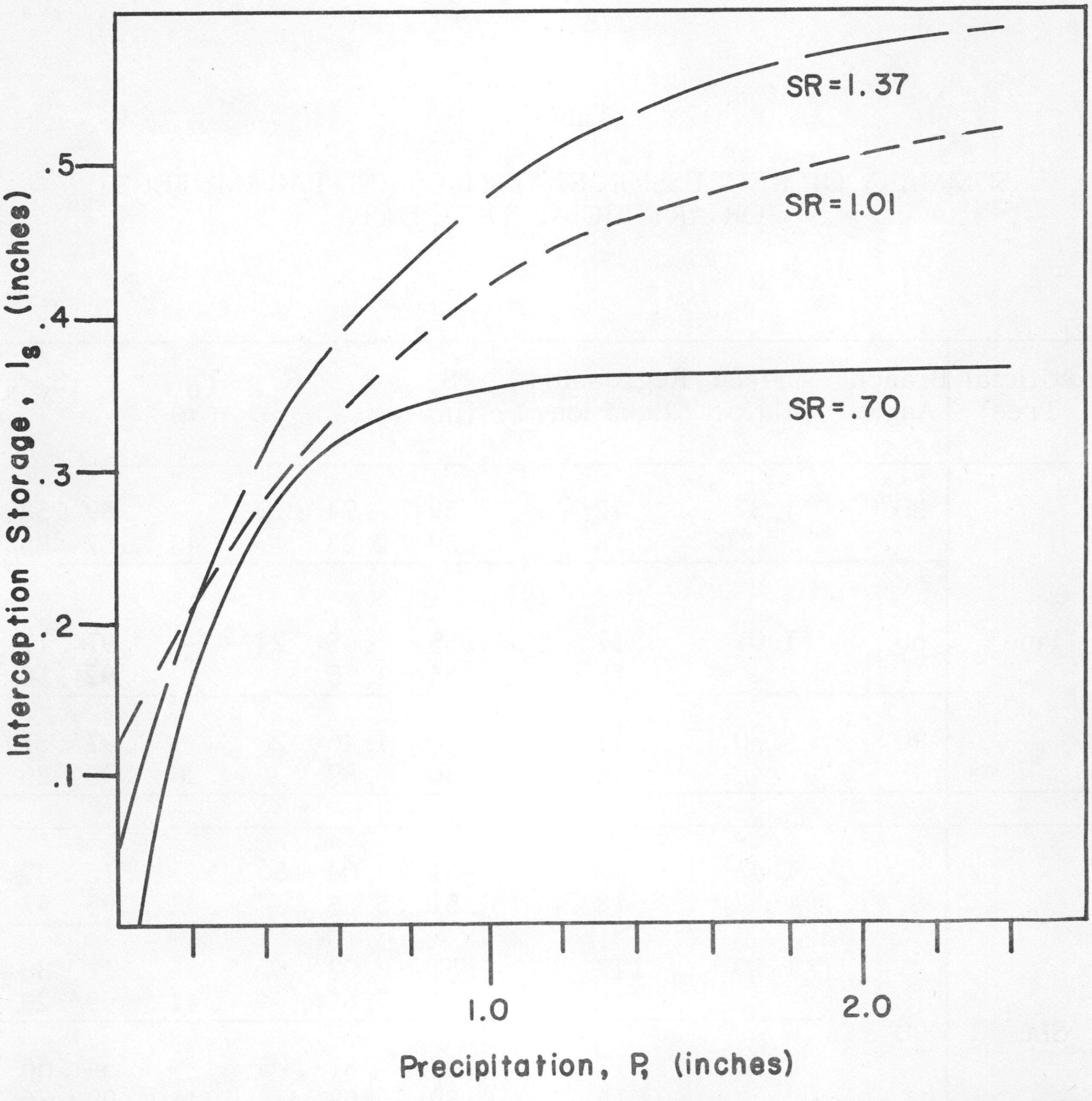

Figure 3. Interception by artificial "pine" trees, with different SR, computed using equation 17. SR of 1. 37, 1. 01 and .70 correspond to branch angles of 30, 60 and 90 degrees, respectively.

branch angles decrease, interception increases for a given amount of precipitation. In Figure 4, similar curves are shown based upon equation 18. No particular significance is attached to the fact that the non-sigmoid curve of Merriam provided the better fit since the difference in goodness of fit was small. Hence the sigmoid curve form, equation 18, with $P_o = 0$ yields results similar to the exponential form of Merriam, equation 17.

Slat Tree Data

Curves of interception as a function of precipitation for the slat tree data of Table 1 are shown in Figure 5. Parameters for these fitted curves are summarized in Table 3. As in the case of the artificial "pine" trees, interception storage for the slat trees generally increased with increasing surface ratio. As indicated by the r values in Table 3, equation 18 provides a good fit to the data. This suggests that (1) the sigmoid curve, with its initial rapid interception increase, is appropriate for the slat trees and (2) that the bridging effect of snow on branches may be a sufficient but not a necessary condition for the initial increase in the interception curve. This lends credence to the previously advanced hypothesis that such increases were due to increases in effective surface cohesiveness due to deposited snow.

Inspection of the regression parameters in Table 3 indicates: (1) maximum storage, S, increases with the surface ratio, SR;

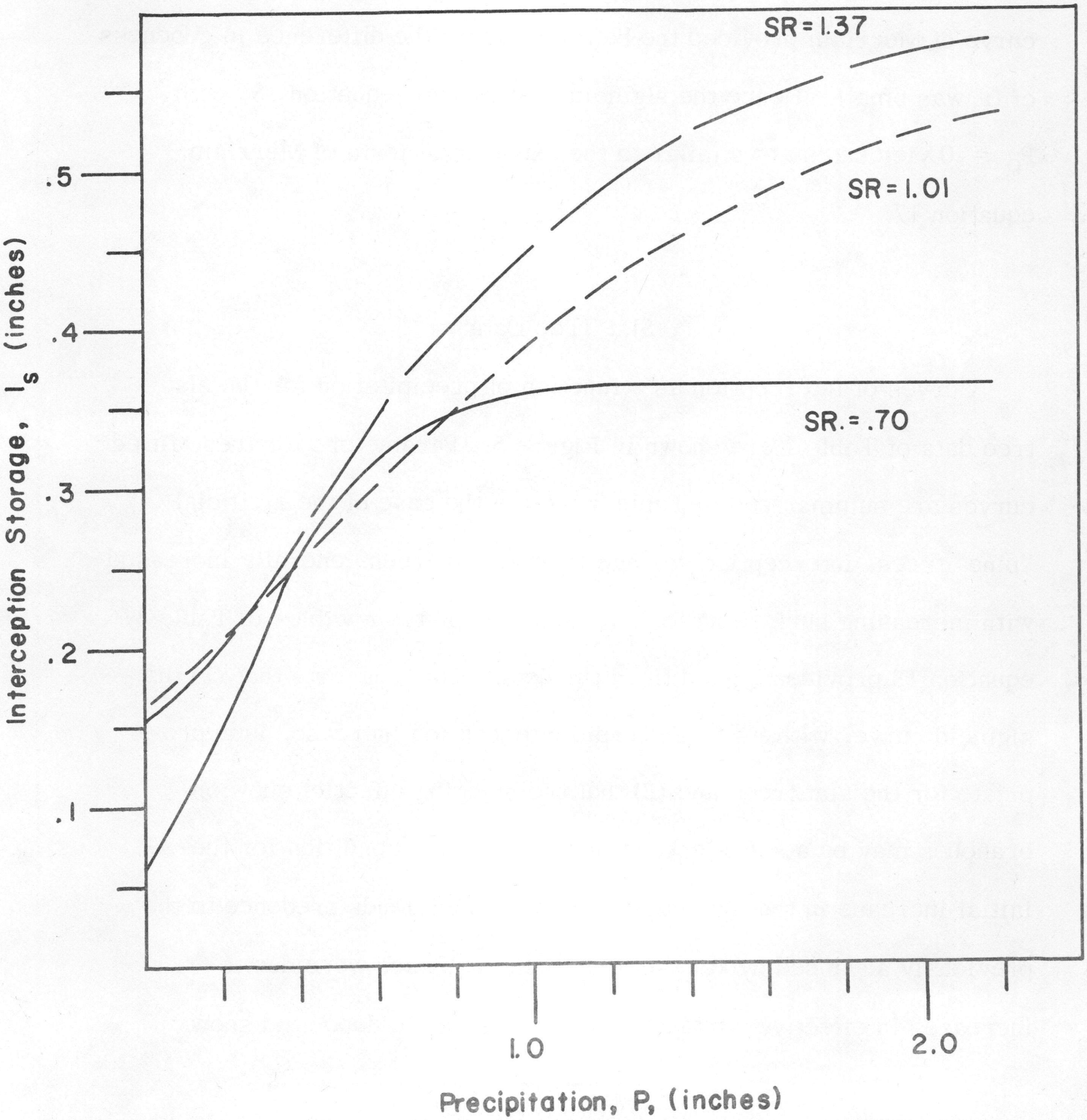

Figure 4. Interception by artificial "pine" trees, with different SR, computed using equation 18. SR of 1.37, 1.01 and .70 correspond to branch angles, 30, 60 and 90 degrees respectively.

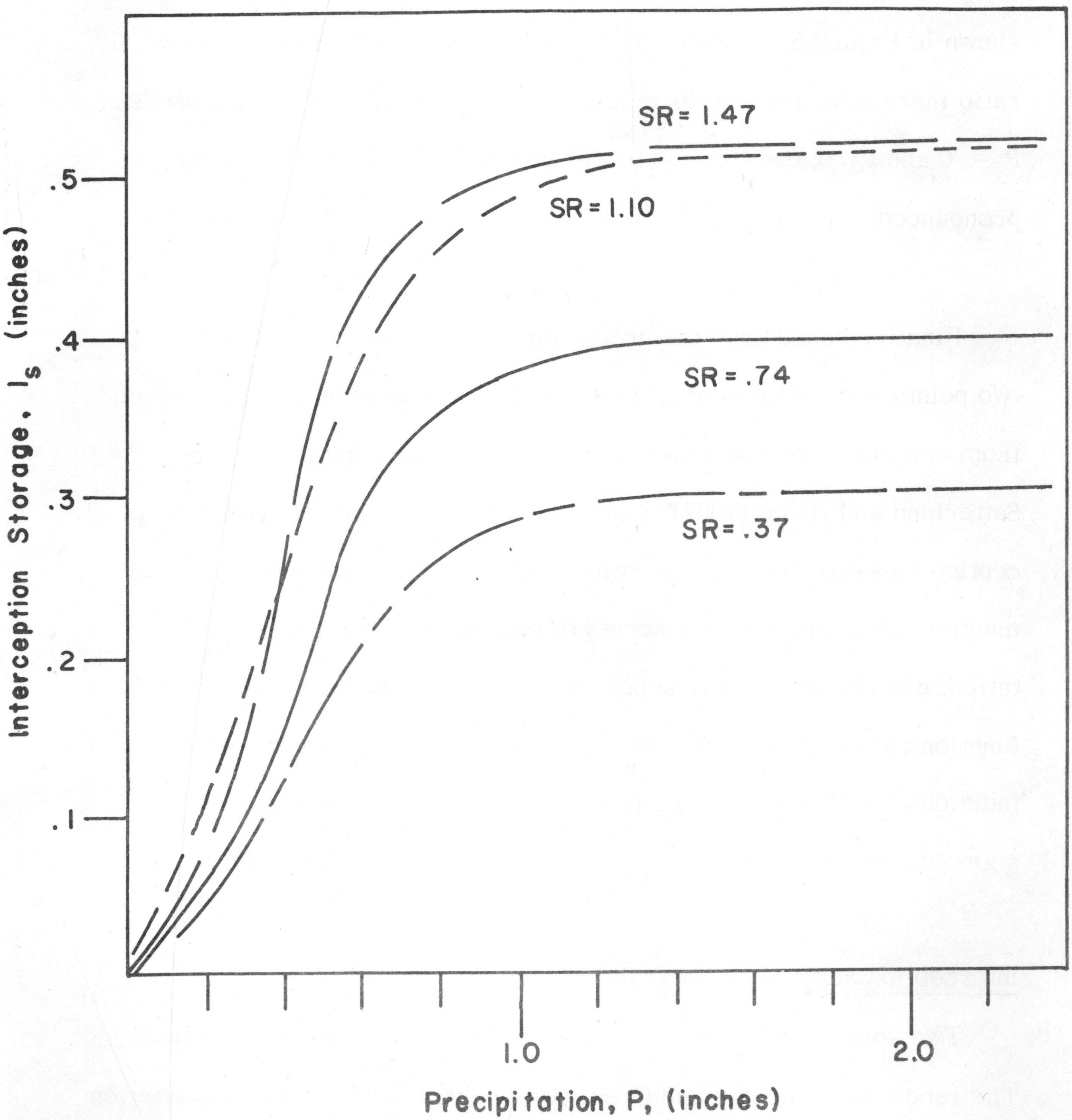

Figure 5. Interception by slat trees computed using equation 18. Branch angles for all SR were 90 degrees.

(2) the magnitude of change in storage as a function of surface ratio decreases as surface ratio approaches 1. 0; and (3) the ratio of k/SR decreases with increases in surface ratio. These relationships are shown in Figure 6. Figures 4 and 5 also suggest that as the surface SR ratio increases, the curves evidence more definitive curvature between $P = 0$ and P_o, i. e. , that the initial increase in interception is more pronounced.

Finally, based upon the preceeding analysis of artificial tree data two points need emphasis: (1) the sigmoid interception curve, derived from continuous measurements of a single tree during a storm by Satterlund and Haupt (1967), can also be derived from averaged interception measured on several similar trees and precipitation measurements made at the end of a series of storms of varying total precipitation; and (2) there would appear to be at least two interception functions, $\psi(P)$, which have reasonable predictive capability for individual trees: Merriam's (1960) equation (equation 3) and the sigmoid curve (equation 4).

Interception Storage on Natural Trees

Two sources of snow interception data for conifers were found. The report by Wanatabe and Ozeki (1964) contained data on two varieties of *Cryptomeria japonica*: *Kumasugi* and *Bokasugi*. The second source,

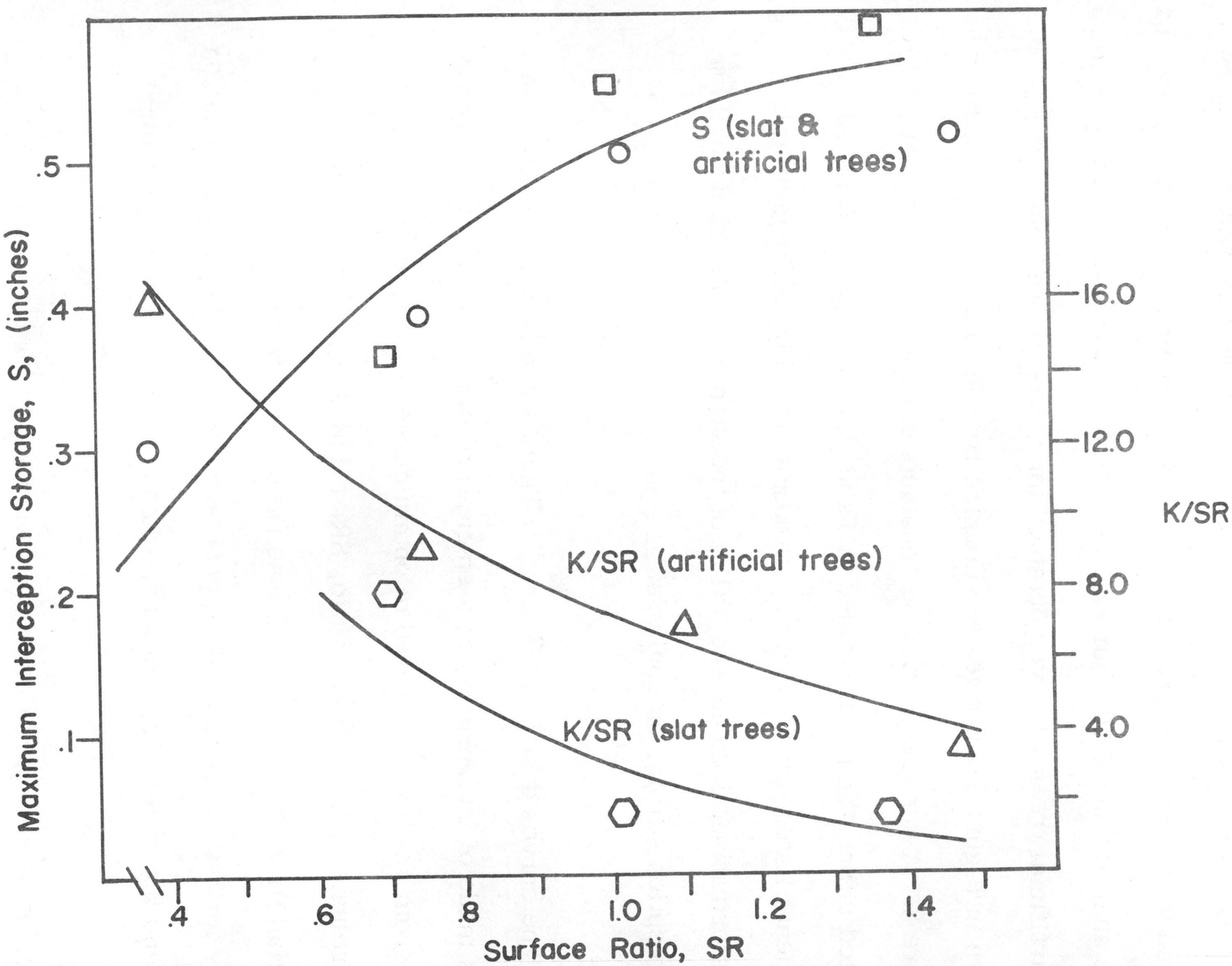

Figure 6. Changes in S and the ratio k/SR as related to SR for artificial tree data.

Satterlund (1973, personal communication), contained data on Douglas fir and white pine interception. These data, summarized in the Appendix, were analyzed using the same regression procedures described previously for artificial trees. Curves obtained for Bokasugi and Kumasugi are shown in Figure 7. Curves for Douglas fir and white pine appear in Figure 8. A summary of curve constants obtained by regression and related information in contained in Table 4. The high correlation coefficients listed for each curve, although biased by the logarithmic transformation, indicate the utility of the sigmoid curve in describing interception storage on conifers.

The curves described by data in Table 4 are based upon observations made of interception on a single tree in contrast to the averaged data from several trees used to obtain curves for the artificial trees. Unfortunately, the surface ratio, SR, could be obtained only for the Douglas fir and white pine. These ratios were 5. 74 and 1. 2 respectively for the saplings used. Conclusions with respect to the variation of S and k with SR are, however, impossible with only single values.

Examination of the interception curve parameters for Cryptomeria in terms of maximum interception storage, S, shows that S relative to tree age increases substantially for the first 30 years and then remains relatively constant. Maximum storage is different for the two varieties. Bokasugi has about 2. 5 times the storage capacity of

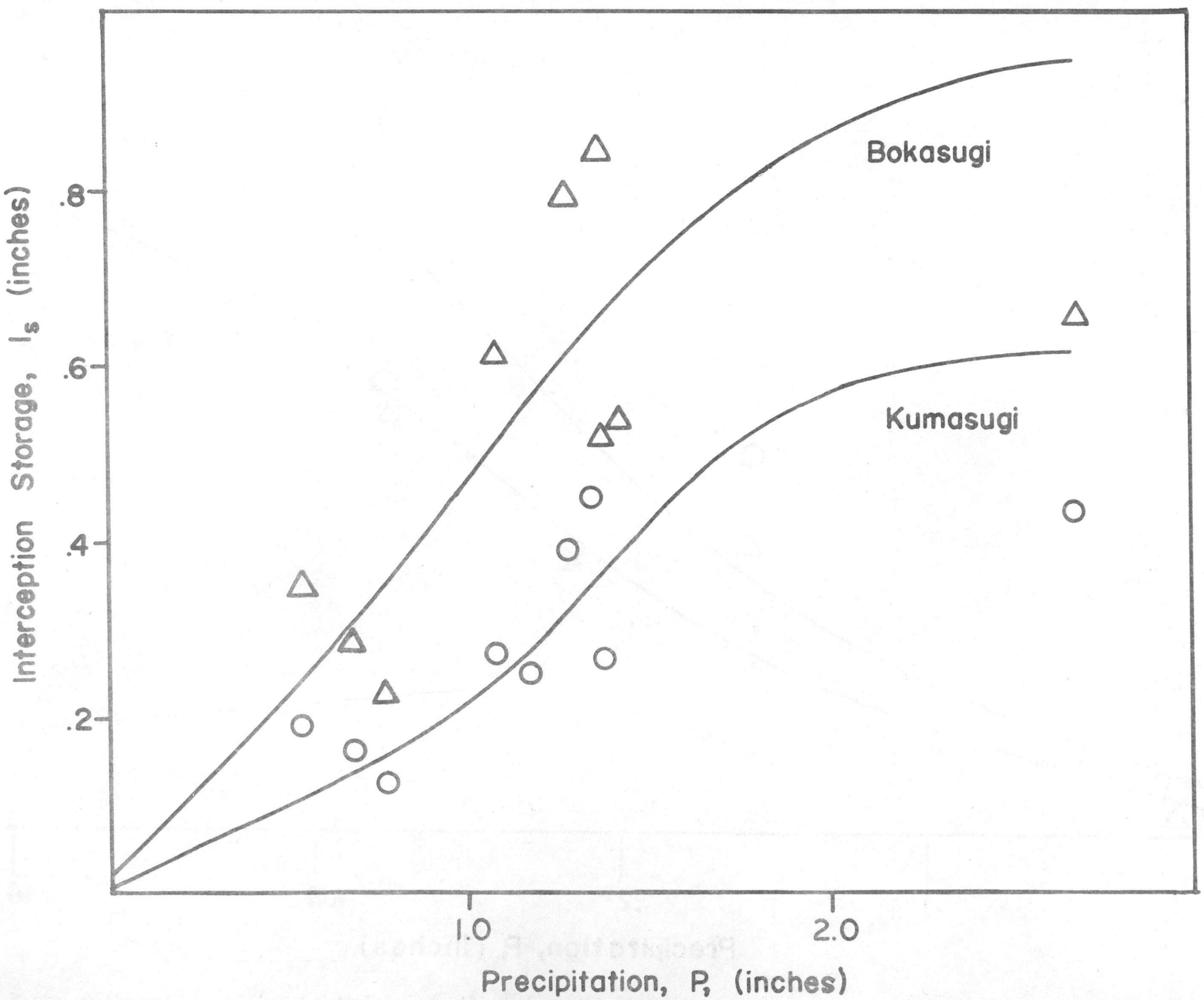

Figure 7. Sigmoid Interception curves for two varieties of Japanese cedar: Bokasugi and Kumasugi. Data source, Watanabe and Ozeki.

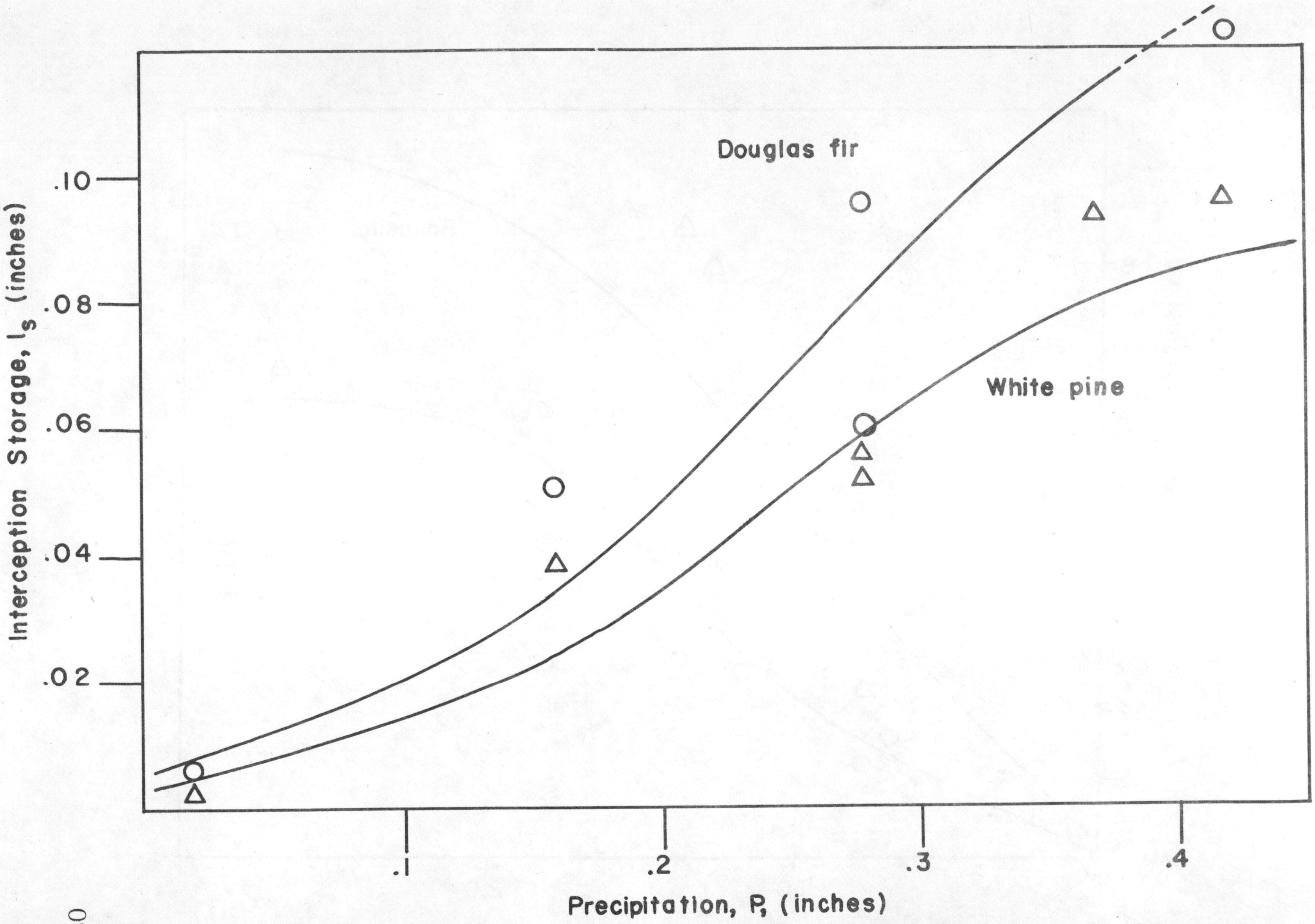

Figure 8. Sigmoid interception curves for Douglas fir and White pine. Data Source, Satterlund.

Table 4.

Summary of Regression Statistics and Parameters

for Real Trees 1/ Using Sigmoid Interception Curve 2/

Data Source	Species	Treatment	No. of Storms	S (in.)	k	Crown Proj. ft.^{2}	Po (in.)	r	Sy.x
1	White Pine	none	7	.094	13.79	89	.05	.96	.46
	Douglas Fir	none	7	.146	11.60	78	.29	.96	.46
		Age 10 yr.	12	.45	3.04	--	.46	.90	.32
		Age 24 yr.	12	.52	3.66	--	.43	.91	.35
		Age 32 yr.	12	.59	3.25	--	.44	.91	.33
		Age 43 yr.	12	.58	3.13	--	.53	.92	.27
		Age 57 yr.	12	.62	3.12	--	.56	.85	.40
2	Japanese Cedar	Variety Numasugi	11	.44	2.17	--	.84	.90	.60
		Variety Bokasugi	11	1.05	2.08	4/	1.04	.82	.61
	1	control 3/	11	.50	1.70	77	.25	.93	.34
	2	1/3 pruned	11	.34	.72	41	.42	.92	.31
	3	1/2 pruned	11	.35	.84	26	.66	.77	.72
	4	1/3 thinned	11	.39	.64	65	.17	.85	.56
	5	1/2 thinned	11	.50	.69	58	.38	.82	.66

1/ Data Sources:
(1) Satterlund and Haupt (personal communication) and (2) Wanatabe and Ozeki.

2/ Equation 18.

3/ Treatment of Kumasugi crown by completely pruning lower 1/3 or 1/2 crown and by overall thinning of 1/2 or 1/2 crown.

4/ Crown projection varied by storm. For Bokasugi a 20% increase was observed while for Kumasugi a 40% decrease.

Kumasugi. In terms of pruning the reduction in S was about 40 percent. The effects of thinning were variable, but reduction in S occurred. Changes in k were evident in terms of (1) a reduction in k with both thinning and pruning and (2) a rapid increase in k up to about 25 years and then a gradual decline. The preceeding relationships are offered not as new interpretations of the data, but as evidence that changes in the sigmoid interception curve parameters can be interpreted in terms of physical differences in the tree species studied.

While admittedly the interpretation of variation in the curve parameters is somewhat speculative, the analysis does suggest that more detailed study of vegetational classes, e. g. age-classes, basal-area classes, form-classes, species, etc. , could provide more precise interpretation. When such relationships are defined, families of interception curves, ψ (P) could be derived such that ψ (P) became ψ (P, SR, Species, age-class, etc.) and interception models for complex stands could be written.

Stand Interception Model

Ideally, a stand interception model would require a minimum of input data which is available with nominal effort and expense. Such a model is proposed here. Basically four types of information would be required to predict interception storage, I_S, accumulated by a stand during a series of storms (effectively over time). First would be the amount of precipitation per storm, second would be the type and composition of vegetation involved by classes, and third the functional relationships ψ (P) relating the I_S to P for each of the classes. Finally, rationale for defining collective interception by the subcomponent classes of the stand would be required.

Precipitation measurements are normally available, although adjusting these to reflect climatic and topographic effects influencing a particular locale may present difficulty. Forest stand composition data by species, age, etc., are frequently available as portions of timber management plans. Previous sections of this paper have suggested forms of the interception function, ψ(P). The remaining requirement then is rationale for the collective interception process.

The simple rationale suggested by Khil'mi is that the whole is equal to the sum of its parts, i.e., that total interception by the stand can be represented by a properly weighted summation of the interception functions of single trees, ψ(P). More accurately, total interception can be defined as the weighted summation of stand components, whether they be defined by age-class, form-class, habitat type or other characteristics. Such logic not only has the appeal of simplicity but of flexibility since any type of descriptive vegetational data can be used provided appropriate ψ(P) are defined. Such an approach is valid only to a good approximation if (1) the interception process for individual stand components is independent of the process on surrounding components or (2) the net process of interaction or redistribution approaches zero within the stand. The latter assumption seems more probable and is taken here as a working assumption.

When forms, $\psi(P)$ which approach a maximum, S, as $P = Q_i$, are used in equation 9 it can be rewritten as:

$$I_i = \gamma_i A \int_0^P \psi_i (P) dP \tag{19}$$

where A is the stand Area and γ_i is the stems in subclass i per unit area. Equation 8 then becomes:

$$I_t = \sum_{i=1}^{n} I_i(P) \tag{20}$$

with n being the number of vegetation classes.

With the product $\gamma_i A_t$ providing weights for each stand component, equations 19 and 20 then comprise the stand model.

Examination of the Stand Model

It was not possible to validate the stand model, i. e. to test the basic rationale of summation of parts (refer page 33) using the same data for both compilation and verification. Internal error in the model due to the interaction of weighting effects, e. g. stand composition, size of storm-record length and the interception function $\psi(P)$ could, however, be illustrated in terms of the available data as they influence the predictibility of I_S.

The procedure is as follows:

1. Select trees at random from Tables 1 and 2 to simluate a stand of mixed trees, slat and artificial.

2. Select storms (precipitation) at random from Tables 1 and 2 to synthesize a seasonal storm-record.

3. Compute total snow intercepted during the storm season by (1) summing measured interception recorded in Tables 1 and 2 and (2) using the appropriate (P) defined in Table 3. (Sigmoid forms were used for all ψ (P) except in case of the artificial "pine" tree data where equation 3 was used). The difference in the two estimates, ΔI_S, was then taken as the expression of model error. Model error, ΔI_S, was expressed as a percent of measured I_S as shown in Table 5. Except for run 4, error was significantly less than 10 percent. Best results were obtained for the mixed stand with the greater number of trees and storms (run 1). The greatest error (13.7 percent) occurred not with the smallest number of storms, run 6, nor the smallest number of trees, run 5, but with run 4. This is attributed to the random combination of ψ(P) with greater Sy. x and the larger storms due to sampling. Runs 1 - 6 generally suggest smaller stand size and various stand mixtures result in larger prediction error. Runs 4 - 6 suggest that size of stand influences I_S more than length of storm-record.

Table 5.

PREDICTION OF INTERCEPTION BY USING
ψ (P) AND STAND MODEL

Run	Simulated "STAND" Composition	Simulated Storms of Record	I_s (in.)	Percent error
1	8 slat, 12 "pine"	1-7	.17	.4
2	8 slat	1-7	.22	1.3
3	12 "pine"	1-7	.40	1.4
4	4 slat, 3 "pine"	1-3, 6, 7	1.98	13.7
5	3 slat, 2 "pine"	2-5, 7	.84	7.8
6	3 slat, 2 "pine"	4, 6	.44	8.0
7	1 Douglas fir 1 White pine	1-6	.06	7.2
8	1 Japanese cedar from each of five age-classes	12	3.34	13.4
9	1 Bokasugi 1 Kumasugi	12	1.06	8.5
10	2 pruned Japanese cedar 2 thinned Japanese cedar	11	1.45	10.3

Similar procedures were used to examine simulated stands and storm records for the natural tree data. Errors in prediction also appear in Table 5. The fewer trees per simulated stand, a result of fewer observations available from the literature, are the primary cause of the larger prediction errors recorded using the natural tree data. It seems probable that had more trees been measured and the stand size increased, prediction error for the natural trees would have been of the same order of magnitude as that generally obtained for the artificial trees. This would certainly be indicated by the fact that the Sy. x obtained for ψ(P) for natural trees were of the same order of magnitude as those obtained from artificial tree data.

CONCLUSIONS

Analysis of interception data for artificial and natural trees in this study indicates:

1. That physical models can be used to qualitatively define relationships between interception storage, I_S, and descriptive vegetational parameters.

2. That the surface ratio, SR, is a useful parameter in defining the differences in sigmoid curve parameters k and S.

3. That at least two forms of the interception function ψ (P), defined by equations 3 and 4, are useful in modeling.

4. That the sigmoid interception curve, equation 4, can be defined from measurements of precipitation and interception made at the end of each of a sequence of storms rather than continuous.

5. That bridging of snow on tree branches is not a necessary condition for development of the initial interception increase of the sigmoid curve.

6. That the stand model described here offers a means of describing the accumulation phase of the interception process.

Based on the several simulation runs comparing the model results with the actual measurements of interception storage, the model evidences reasonable predictive potential. Clearly error is reduced for the greater number of storms and trees.

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APPENDIX

Table 1.

SNOW INTERCEPTION BY PRUNED AND THINNED JAPANESE CEDAR [1]

Month	Day	Snow Density	Snow (in.)	Interception (in.) control (5. 7) [2]	1/2 pruned (5. 6)	1/3 thinned (5. 5)	1/3 pruned (4. 9)	1/2 thinned (4. 4)
Jan.	15	.08	3.71	.64	.70	.53	.51	.64
	20	.10	.60	.32	.32	.22	.20	.27
	22	.08	4.48	.61	.52	.38	.35	.49
	27	.11	3.59	.50	.34	.31	.31	.33
Feb.	19	.08	.47	.24	.15	.18	.14	.19
	20	.08	.92	.41	.36	.37	.34	.36
	21	.09	2.04	.48	.35	.34	.34	.40
	22	.10	.59	.37	.28	.24	.23	.30
	26	.07	1.25	.38	.28	.25	.20	.30
	28	--	.69	.32	.28	.29	.17	.31
March	11	.10	.49	.32	.22	.28	.17	.28

1/ Data from Table 8, p. 132, Watanabe and Ozeki (1967).

2/ Figures in parenthesis are crown projection in m^2.

Table 2.

1967 SNOW INTERCEPTION STORAGE, I_s, PRIEST RIVER EXPERIMENTAL FOREST

(Supplied by D. Satterlund)

Month	Day	Precipitation (in.)	I_s (in.) (DF)	I_s (in.) (W. R.)
1	12	.37	.146	.094
1	18	.42	.123	.096
1	19	.28	.060	.053
1	22	.02	.006	.003
1	25	.28	.098	.056
1	26	.16	.051	.039

Table 3.

SNOW INTERCEPTION BY DIFFERENT AGED JAPANESE CEDAR 1 /

Year & Month	Day	Density	Snow Fall	Interception (in.) Age (yr.) 10	20	32	43	57
1962								
	11	0. 07	. 88	. 35	. 41	. 44	. 43	. 41
Dec.	22	--	. 75	. 31	. 39	. 44	. 37	. 37
	24	--	. 33	. 19	. 24	. 25	. 22	. 20
1963								
	8	0. 13	1. 55	. 83	1. 15	1. 16	. 94	. 81
Jan.	21	0. 07	. 66	. 31	. 37	. 38	. 34	. 43
	29	0. 08	. 90	. 39	. 48	. 53	. 44	. 51
	6	0. 07	. 74	. 24	. 36	. 37	. 34	. 27
	9	0. 09	. 87	. 45	. 52	. 71	. 58	. 62
Mar.	18	0. 06	. 47	. 21	. 22	. 29	. 21	. 23
	26	--	. 28	. 18	. 22	. 23	. 19	. 20
Apr.	1	--	. 54	. 26	. 32	. 39	. 31	. 39
	3	--	. 75	. 45	. 52	. 59	. 46	. 46

1 / Taken from Table 5, p. 129, of Wanatabe and Ozeki (1967).

Table 4.

SNOW INTERCEPTION BY TWO VARIETIES OF JAPANESE CEDAR [1/]

Month	Day	Precip.	Density	Interception (in.) Variety Kumasugi	Bokasugi
1960					
Dec.	6	1. 26	0. 09	. 39	. 80
	18	1. 35	0. 07	. 45	. 85
	26	6. 52	0. 10	. 88	1. 26
1961					
Jan.	4	0. 54	--	. 20	. 35
	6	1. 53	0. 09	. 72	1. 26
	16	1. 09	0. 09	. 28	. 61
	22	2. 64	0. 10	. 43	. 66
	25	0. 77	--	. 12	. 22
Feb.	1	1. 17	0. 12	. 26	. 54
	3	1. 43	--	. 38	. 54
	8	1. 37	0. 15	. 27	. 52
	9	0. 70	0. 13	. 17	. 29

1/ From Table 3, p. 125, of Wanatabe and Ozeki (1967).

Part II:

LABORATORY MODELING OF SNOW INTERCEPTION ON TREES

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September, 1973

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ABSTRACT

This portion of the study was conducted to determine the interception characteristics of both artificial and real trees using artificial snow. A drum apparatus was constructed to allow artificial snow to be dropped over the trees. Sawdust, soap flakes, and shredded polyethelene were tested as artificial snow with the polyethelene giving the best results.

It was found that for three foot high artificial trees, the smaller branch angles intercept more snow than larger branch angles in terms of inches of interception over projected areas of the tree. Also the shape of the interception versus precipitation curve is the same for both real and artificial trees except that the amounts are considerably less for real trees. For three and six foot ponderosa pine, Douglas fir, and concolor fir there was no appreciable difference between the interception-precipitation curve for the two heights of each species.

TABLE OF CONTENTS

CHAPTER	PAGE
INTRODUCTION AND PURPOSE	46
PAST WORK	47
METHODOLOGY	49
A. Snow Tests	49
B. Experimental Equipment	51
1. Snowfall Apparatus	52
2. Trees	54
RESULTS AND DISCUSSION	57
A. Interception on Artificial Trees	57
B. Interception on Real Trees and Comparison with Artificial Trees	61
C. Tests on Individual Branches	62
CONCLUSIONS AND RECOMMENDATIONS	65
REFERENCES	67
APPENDIX: ILLUSTRATIONS	68

LIST OF TABLES

TABLE PAGE

Table 1. Size distribution of shredded polyethelene snow. 52

Table 2. Variation of snowfall intensity with time 53

Table 3. Summary of tree types used for interception tests . . . 56

Table 4. Characteristics of branches used in branch interception tests. 63

INTRODUCTION AND PURPOSE

The subject of interception of snow on trees is one of considerable interest to hydrologists. This amount of precipitation is usually considered a loss to the watershed and is considered as water not available for runoff from the basin. It is very difficult to do field studies of the many parameters which will influence interception, especially if it is desired to separate the factors due only to tree or meteorological factors. It is also difficult to use real snow and full size trees in a laboratory. Thus some compromise needs to be made in any interception study.

The general purpose of this study was to model the snow interception process in the laboratory. The following specific objectives were pursued:

1. Find and test a suitable substitute for snow which can be used for interception studies.
2. Determine a possible method for depositing snow on trees.
3. Determine the effect of branch angle of artificial trees on the interception of artificial snow on model trees.
4. Compare the snow interception pattern between artificial model trees and real trees of typical Christmas tree size.

PAST WORK

Model tests with many types of artificial snow have been conducted for many years. All of these were concerned with either drifting snow or modeling snow catch in precipitation gages.

Warnick (1956) used sawdust to simulate snow in an attempt to determine the effect of wind on the gage catch of snow. The size of sawdust was picked to have the same terminal velocity as real snow. This was the only scaling parameter used. Whiffin and Price (1954) used sawdust to study the best shape for a snow plow blade. The use of sawdust is criticized because sawdust does not have the same coefficient of restitution (the ratio of velocity of rebound to fall or impact velocity) as real snow ($\approx .55$) (Gerdel and Strom, 1961). While studying a rain-snow discriminator, McKean (1969) used styrofoam particles to simulate the reflectance properties of snow.

Many studies have been conducted on the use of artificial snow for various drifting studies (Gerdel and Strom, 1961; Strom and others, 1962). For these drifting studies, borax has proven to be the best imitator of drifting snow. The borax best models the coefficient of restitution as well as the scaled full velocity and size of particle.

No studies were found using artificial snow to model interception. None of the above cited references attempted to use artificial snow as a falling material, only as a drifting material.

METHODOLOGY

No studies were found using artificial snow to model interception. Only sawdust was used to simulate falling snow but this was used as blown snow. Since the desired end result was to not only simulate snow but also to simulate the snow-tree interaction, some tests were necessary to determine a suitable material for this study. Once this material was found, suitable experimental apparatus was devised and constructed.

A. Snow Tests

Three materials were tested as a substitute for snow: sawdust, soap flakes, and shredded polyethelene film.

The sawdust was screened of coarse material and dust. The soap flakes were a commercially available product (trade name: Ivory Flakes). These were thin flakes about 1/8 to 1/4 inch square. These were not sieved but used directly from the box. The third material is available from theatrical hardware supply houses and is used in theater and television production to simulate falling and blowing snow. It is approximately 1 mil thickness and is made by grinding the sheets of film through a 5/16 inch screen. A whitening agent is added.

The original test apparatus was a platform (Fig. 1) with a vibrator attached to a pegboard. The artificial snow was put on the platform and the vibration forced the material through the holes. The number and size of holes were varied depending on the size distribution of the material tested.

The sawdust was discarded almost immediately. It did not fall through the holes well and produced a "capping" effect over the holes. Most importantly, it did not land and hold on the tree branches like real snow. The individual particles would fall through the needles rather than be intercepted as expected.

The soap flakes were extensively tested and some of the actual results of interception with the soap flakes are presented later. Figure 2 shows an artificial tree after a test run with the soap flakes. The soap flakes did not appear to build up in a "capping" fashion in the same manner as freshly fallen snow. The observation was made that the soap flakes were very slippery and would slide if the flakes were piled very deeply over a branch. The soap flakes would also settle within the needles rather than be caught by them. These flakes did have two objectionable features: the individual flakes broke into small pieces very easily and the fine particles were very irritating to the nose and eyes.

The shredded polyethelene was tested in a similar manner and performed very well (Figure 3). The visual effects of this snow compare very favorably with real snow, especially in the manner in which it accumulates on the tree, the mounding effect as it is caught, and the manner in which the individual particles are caught by the needles.

Because the shredded polyethelene appeared to fulfill some of the requirements for artificial snow, the density and size distribution of this material was determined. The percent retained on each sieve is recorded in Table 1. This table is for snow which had been used and may not be representative of never-used snow. The density of the material as it accumulated on the floor of the laboratory was measured as 0. 050.

B. Experimental Equipment

The equipment necessary for this experiment consisted of a snowfall apparatus and the trees. The snowfall apparatus was constructed in the engineering shop while some trees were purchased and some were built to specification.

Table 1. Size distribution of shredded polyethelene snow.

Size of opening (inches)	Percent retained on sieve of indicated size
.185	0.3
.131	10.2
.093	27.2
.078	13.3
.055	24.3
.046	6.5
pan	18.2

1. Snowfall Apparatus

The snowfall apparatus is shown in Figures 4 and 5. The overall design is patterned after a theatrical design. The screen is 1/4 inch mesh wire screen and allows all but the coarser material to pass through. The gearbox and motor are connected by a set of stepped pulleys which were used to vary the drum speed which was finally fixed (after some testing) at 4 rpm (Figure 6). The cylinders were one foot in diameter and the total height of the apparatus is 12 feet.

Table 2. Variation of snowfall intensity with time.

Elapsed time (minutes)	Intensity (iph)	Elapsed time (minutes)	Intensity (iph)
0	0	45	2. 47
5	2. 15	50	7. 32
10	1. 08	55	3. 77
15	1. 18	60	4. 09
20	0. 97	65	11. 84
25	1. 40	70	10. 98
30	1. 61	75	8. 39
35	1. 72	80	4. 30
40	2. 37	85	2. 47
		90	1. 83

The variation in snowfall intensity is shown in Table 2. Because of the variation in the intensity, the size distribution of the snow was checked at three times, 0-5, 25-30, and 55-90 minutes. The size distribution of the first two tests was the same as given in Table 1 but the 55-90 minute size distribution was shifted significantly towards the coarser sizes with over 90 percent larger than 0. 093 inches. This shift towards the larger sizes may have the effect of increasing the interception in the later parts of the experiment. In comparing this with real interception in the forest, it should be remembered that the first 40 minutes of this test correspond to about one inch of precipitation. This is a fair amount of precipitation and should cover the larger part of the precipitation range found in the forest.

Tests were also conducted to determine the uniformity of coverage of the 6 ft. by 6 ft. area within the snowfall apparatus. Sixteen aluminum pie plates were placed on the floor in a grid pattern. This test resulted in a mean of 49.0 grams per plate and a standard deviation of 11.0 grams. The range was from 23.0 to 63.5 grams. This dispersion was considered acceptable.

The chamber was completely surrounded by a canvas curtain. This prevented air currents from heater fans and open doors from disturbing the experiment. In retrospect, some disturbance may have been beneficial. (Some disturbance of falling "snowflakes" might have been beneficial in increasing the uniformity of the distribution as it fell).

2. Trees

Three basic types of trees were used in this experiment. They were artificial trees, three to six feet tall, and real Christmas trees purchased from local Christmas tree dealers. In addition to using these trees, branches were removed from both the artificial and real trees and used in separate tests.

In addition to using the entire tree for an interception test, some trees were cut to a height of 3 feet and another test was conducted. This then gave a comparison between the entire tree (6 feet tall) and the top of the tree (3 feet tall). Table 3 contains a summary of all tests which were used for the analysis presented here.

The areas indicated are projected area. This was obtained by hanging a bright light 12 feet over the tree and tracing the shadow on a piece of paper on the floor. Care was taken that the area so projected was a true projected area by ensuring the light rays were nearly parallel.

The 30°, 60°, and 90° artificial trees were constructed by Dr. George Belt, College of Forestry, with specific branch angles. These angles were measured from the vertical.

Table 3. Summary of tree types used for interception tests.

Type of Tree	Projected Area (sq in)
30° artificial tree (A)	280
60° artificial tree (B)	488
90° artificial tree (#6)	600
90° artificial tree (#9)	530
Artificial pine top	608
Artificial pine entire	1024
Douglas fir #2 top	436
Douglas fir #2 entire	1490
Concolor fir top	370
Concolor fir entire	1260
Ponderosa pine top	955
Ponderosa pine entire	2016
Grand fir top	436
Grand fir entire	1490

RESULTS AND DISCUSSION

Interception tests were conducted on both artificial and real trees to enable some comparison between the laboratory and the real world. Each type will be discussed separately and then a comparison will be made. All results are presented in graphical form.

A. Interception on Artificial Trees

Two types of artificial trees were used: The specially constructed trees with predetermined branch angles and an artificial "pine" tree which was sold as a "Canada pine" (Figure 7). The Canada pine needles were similar in shape to a grand fir and were constructed of a plastic material. The artificial tree branches and needles resembled a very stiff bottle brush (Figures 2 and 3).

The results obtained from the artificial tree tests are presented in Figures 8 to 15. These figures present the results of the experiments in terms of inches of interception based on projected area of the tree. The accumulated precipitation and accumulated interception were plotted and a smooth curve drawn through the points. For the most of the tests, the weight accumulated on the trees and the precipitation was recorded by an x-y plotter connected to two strain-gage load transducers. Thus the interception curve was continuously plotted. For a few tests, the tree and precipitation weights were read from scales at various time intervals, usually 2 or 5 minutes.

There appears to be a great variability between tests when using the same or similar tree. This is shown in Figure 9 which shows results of two separate tests using the same tree. It is interesting to note that each test resulted in the same saturation value for interception even though each test resulted in a different curve. Figure 11 shows the results of a test with both trees under the snow machine at the same time. The shape of the two curves are similar but slightly displaced.

Examination of each of the figures where the 90° trees were used (Figures 10 to 14) reveals there is also a great variability between both the shape of the interception-precipitation curves and the saturation values attained. Of five tests using 90° trees, the range of saturation values is 1. 4 to 2. 2 inches with most values of 1. 7 or 1. 9 inches. It is significant to note that the accumulated precipitation at the point of saturation clustered around 4 or 9 inches with only one value in between at 6. 5 inches.

The shape of the interception curves has only a very general relationship to the expected shape as described by Satterlund and

Haupt (1967). They developed the concept that interception loss followed a sigmoid growth curve. Figure 11 portrays an approximation to this curve. It is difficult to compare their curves with the present study because of the difference in amounts of precipitation and interception. They sampled storms up to 0.4 inches water equivalent with a maximum interception amount of about 0.07 inches on Douglas fir sapling. A more detailed study than this one would be necessary to determine the shape of the curve, particularly at the low amounts of interception.

Three tests were specifically conducted to compare branch angle effect on interception (Figures 12, 13, 14). A duplicate test was conducted comparing the 30° and 90° branch angle trees (Figures 12 and 13). The 30° and 90° trees were under the snowfall apparatus simultaneously which gives a comparison of the shape of the curves. The two curves of Test 1 (Figure 12) are much closer together than for Test 2 (Figure 13). For Test 2, the 30° tree curve is displaced upwards when compared with Test 1 while the 90° tree (Figure 14) shows little difference between the two trees but the 60° tree definitely does catch more snow than the 90° tree.

Observations made from the curves of Figures 12, 13 and 14 would lead one to conclude that the smaller the branch angle, the greater the interception. That this is not necessarily true is seen from Figure 16 which is a composite of separately conducted tests (Figures 8 through 11). No conclusions can be drawn from this figure as to the effect of branch angle on interception. However, a general trend may be deduced that branch angle does have an effect on interception and that this effect is represented by more interception by trees with smaller angles. This is reasonable because of the cupping effect provided by the upward reach of the branches, especially as the space between needles and even branches begins to bridge over.

The projected area of trees of the same height has an inverse effect on the interception of snow (Figure 17). The values presented are confounded by the branch angle effect. As the area of the tree increases, there is a pronounced tendency for the saturation value of interception to decrease. This does not hold true for the increase in area associated with increasing tree height as shown by the data of Figure 15. In this test the top half and the entire artificial Canada pine tree were tested. The taller total tree caught 150 percent more snow at saturation than did the smaller upper half. It should be emphasized that this tree had a different branch and needle configuration than did the artificial trees used in previous tests (Figure 7).

B. Interception on Real Trees and Comparison with Artificial Trees.

Interception tests were conducted on four different real trees. These were artificial "pine" trees purchased from a local lot. All were 6 feet tall and chosen for shape. Two tests were conducted for each tree whereby the entire tree was tested and then the top 3 feet were cut off and tested again. The areas of tops and entire trees are given in Table 3. The results of the interception tests are shown in Figures 18 through 23.

The general shape of the curves for both entire and tops of trees (Figures 18 and 19) does not differ from the artificial trees. However, the amount of interception is a good amount less than artificial trees especially when compared with the artificial Canada pine tree which is the same height as the real trees. None of the real tree tests were over 2 inches interception while most of the artificial trees approached or surpassed 2 inches.

A possible explanation is that the branch and needle configuration of real trees is not approximated hydrologically by the artificial branches and needles. On a real tree, more of the branches may not contain snow-catching needles while the full length of the artificial branches contained needles.

The entire tree and tops of the trees follow the same general trend; i. e., ponderosa pine, Douglas fir, concolor fir, and grand fir in increasing order of interception. An exception is the grand fir where the top drops in relative position. In both cases, when the Canada pine is added it is above all the interception curves for the real trees. The effect of area on interception is also quite evident. In Figure 18, with the exception of the concolor fir, the trend is from large to small areas while in Figure 19, the single exception is grand fir. This is the same as the trend shown by artificial branch angle trees.

A comparison between the entire tree and the top of trees is shown in Figures 15, 20, 21, and 22. The Canada pine and grand fir give 75 percent more interception to the taller entire tree while all of the rest of the trees show about the same interception for both tests. The ponderosa pine and Douglas fir behave the same in that the curve for the top of the tree intercepts more snow at lower amounts of precipitation and then as saturation is approached, withhold less snow.

C. Tests on Individual Branches.

Different species of trees have different needle and branch characteristics. This is one of the keys in tree identification. This may also be one reason for different interception characteristics of trees. In order to make observations of the effect of these differences on interception some tests were conducted comparing branches of 3 species of real trees and 2 from the Canada pine. Four nearly identical branches of each species were tested as a single whorl tree. Table 4 lists the features of the branches while Figure 24 shows the results of the tests.

Table 4. Characteristics of branches used in branch interception tests.

Branch	Average Length (inches)	Total Projected Area (sq in)
Large Canada Pine	24	458
Small Canada Pine	12	140
Ponderosa Pine	25	544
Douglas Fir	25	310
Western White Pine	13	118

As shown in Figure 24, very little difference is evident in the early stages of interception between western white pine and ponderosa pine. However, the ponderosa pine branch is much larger and carried much more snow at saturation. The Douglas fir branch carried the least amount of snow at saturation. No discernible relationship is evident between branch lengths, projected area, and interception.

On the basis of the branch tests, much more work is needed before it will be possible to extend branch tests to full size or even scale model trees. Mathematical modeling should precede that work.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the tests conducted, the following conclusions are offered:

1. The shredded polyethelene snow is suitable for modeling interception of dry light snow on trees.
2. The drum apparatus is suitable for allowing snow to fall in the same manner as real snow.
3. The branch angle tests showed that the smaller the branch angle, the greater was the interception regardless of precipitation amount.
4. The interception curves of both real and artificial trees are similar in shape except that the real trees intercept less snow.
5. For three and six foot ponderosa pine, Douglas fir, and concolor fir there was no appreciable difference between the interception-precipitation curve for the two heights of each species.

On the basis of experience gained during this experiment, some recommendations can be made. The snow should be sieved to a known uniform size distribution before use to take out the fine and the very coarse material. This may reduce the change in size distribution with time which occurred with the drum apparatus. This shift in size distribution is probably what caused the changes in intensity. A positive feed snowfall device can be easily devised using small augers, chain driver, or a myriad of other devices. Uniformity under those conditions could be encouraged by small reciprocating jaws. If possible, a taller chamber should be used to enable testing of taller trees.

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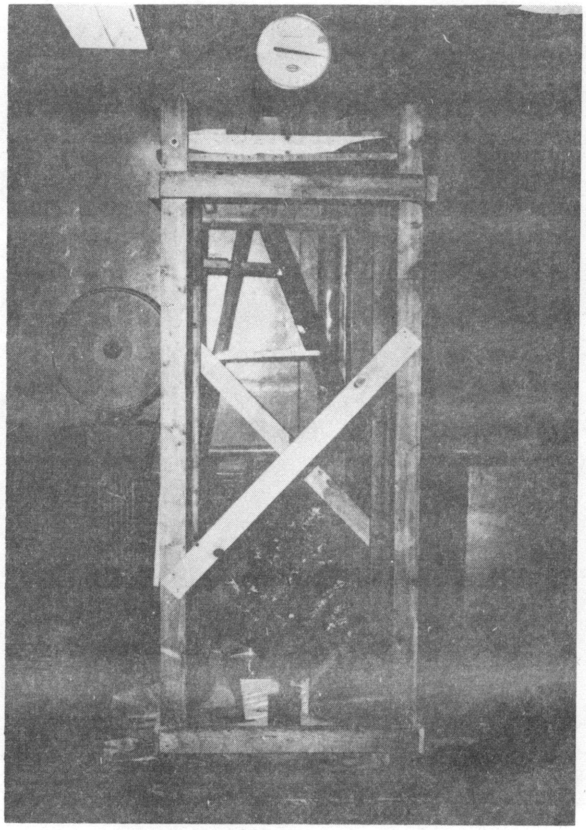
APPENDIX

LIST OF ILLUSTRATIONS

FIGURE		PAGE
Figure 1.	Original snowfall apparatus and vibrating platform. . .	71
Figure 2.	Artificial tree with soap flake snow.	72
Figure 3.	Polyethelene snow on artificial tree.	72
Figure 4.	Basic snowfall apparatus.	73
Figure 5.	View of drums partially filled with polyethelene snow .	73
Figure 6.	Closeup of drum and drive for snowfall apparatus . . .	74
Figure 7.	Branch angles and shapes for artificial Canada pine . .	74
Figure 8.	Interception on an artificial tree with 30 degree branch angle	75
Figure 9.	Test of reproductivity of interception using two 60 degree trees	76
Figure 10.	Interception of an artificial tree with a 90 degree branch angle	77
Figure 11.	Interception on two similar 90 degree trees	78
Figure 12.	Comparison of interception on two trees with 30 and 90 degree angles. Test 1.	79
Figure 13.	Comparison of interception on two trees with 30 and 90 degree branch angles. Test 2.	80
Figure 14.	Comparison of interception on two trees with 60 and 90 degree branch angles	81
Figure 15.	Interception on artificial Christmas tree (Canada pine).	82
Figure 16.	Composite of branch angle tests.	83
Figure 17.	Effect of projected area on interception.	84



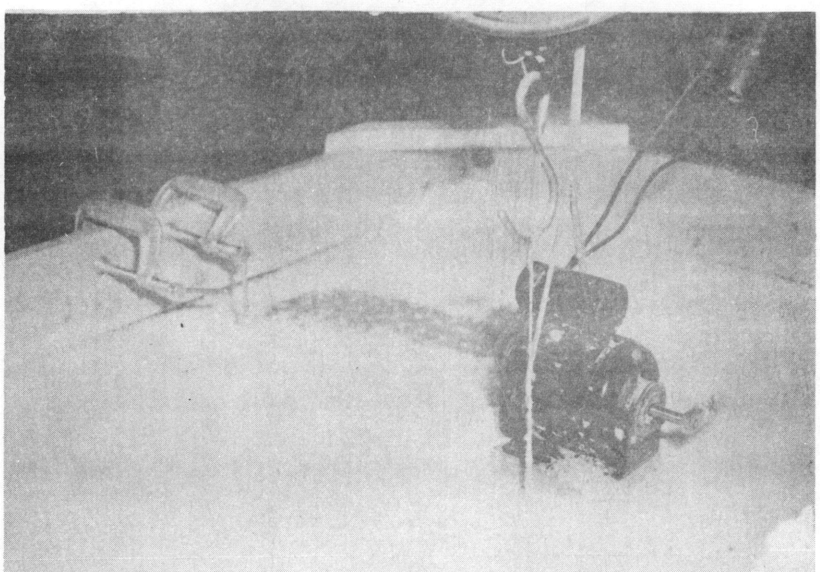


Figure 1. Original snowfall apparatus and vibrating platform.

FIGURE PAGE

Figure 18. Interception tests on entire tree 85

Figure 19. Interception tests using tops of trees 86

Figure 20. Interception on concolor fir 87

Figure 21. Interception on ponderosa pine. 88

Figure 22. Interception on Douglas fir 89

Figure 23. Interception on grand fir 90

Figure 24. Interception on individual branches 91

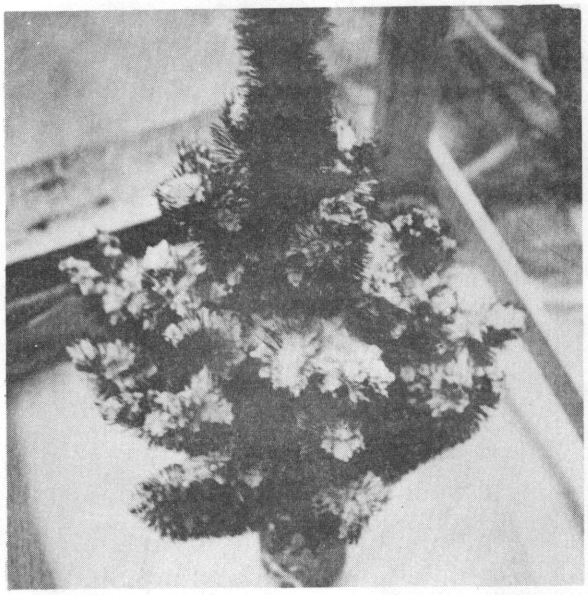


Figure 2. Artificial tree with soap flake snow.

Figure 3. Polyethelene snow on artificial tree.

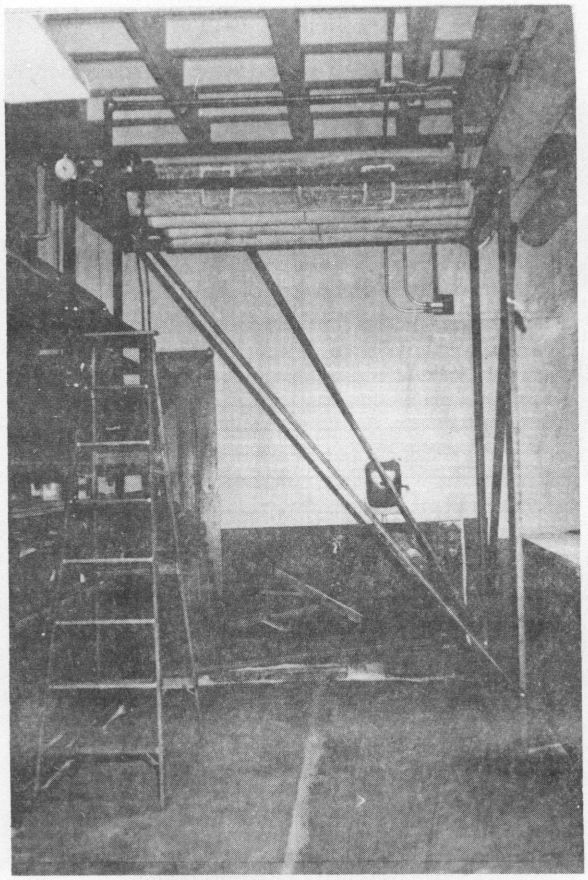


Figure 4. Basic snowfall apparatus.

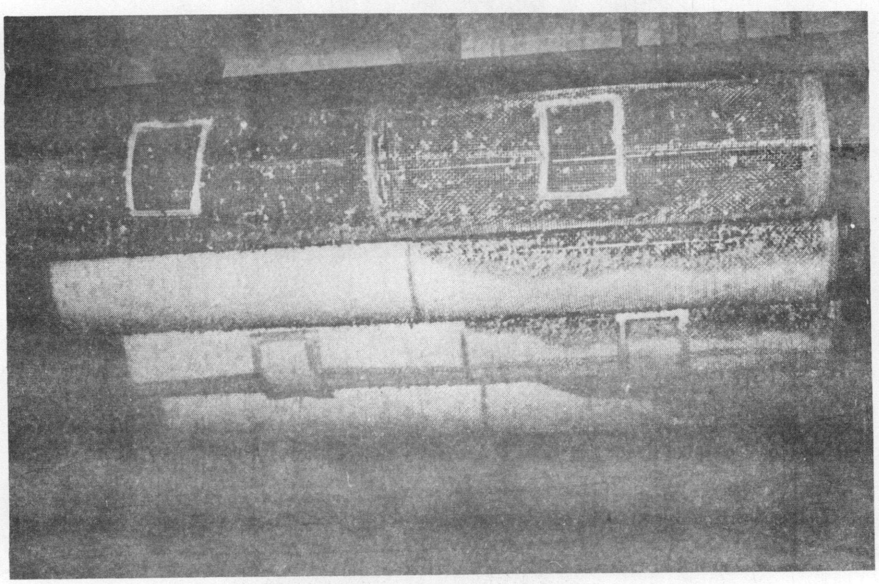


Figure 5. View of drums partially filled with polyethelene snow.

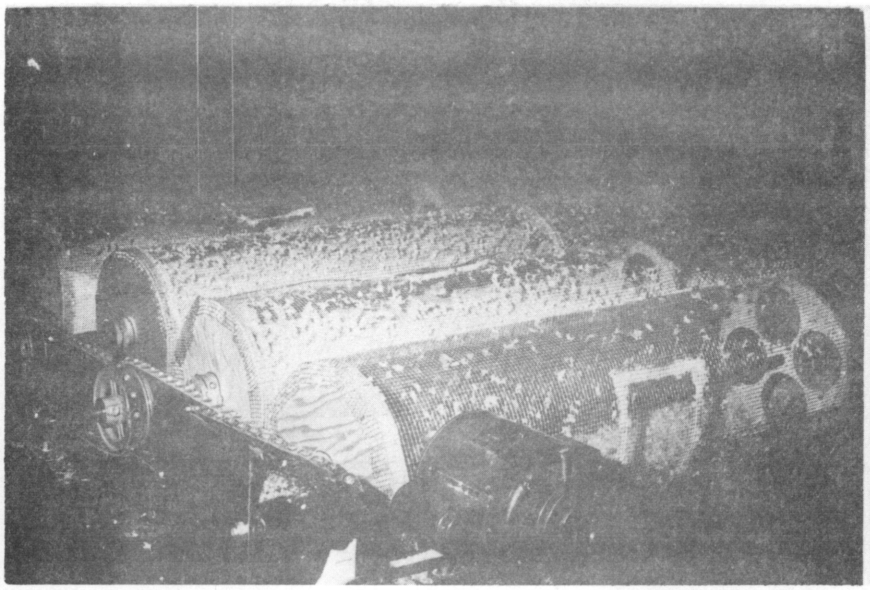


Figure 6. Closeup of drum and drive for snowfall apparatus.

Figure 7. Branch angles and shapes for artificial Canada Pine.

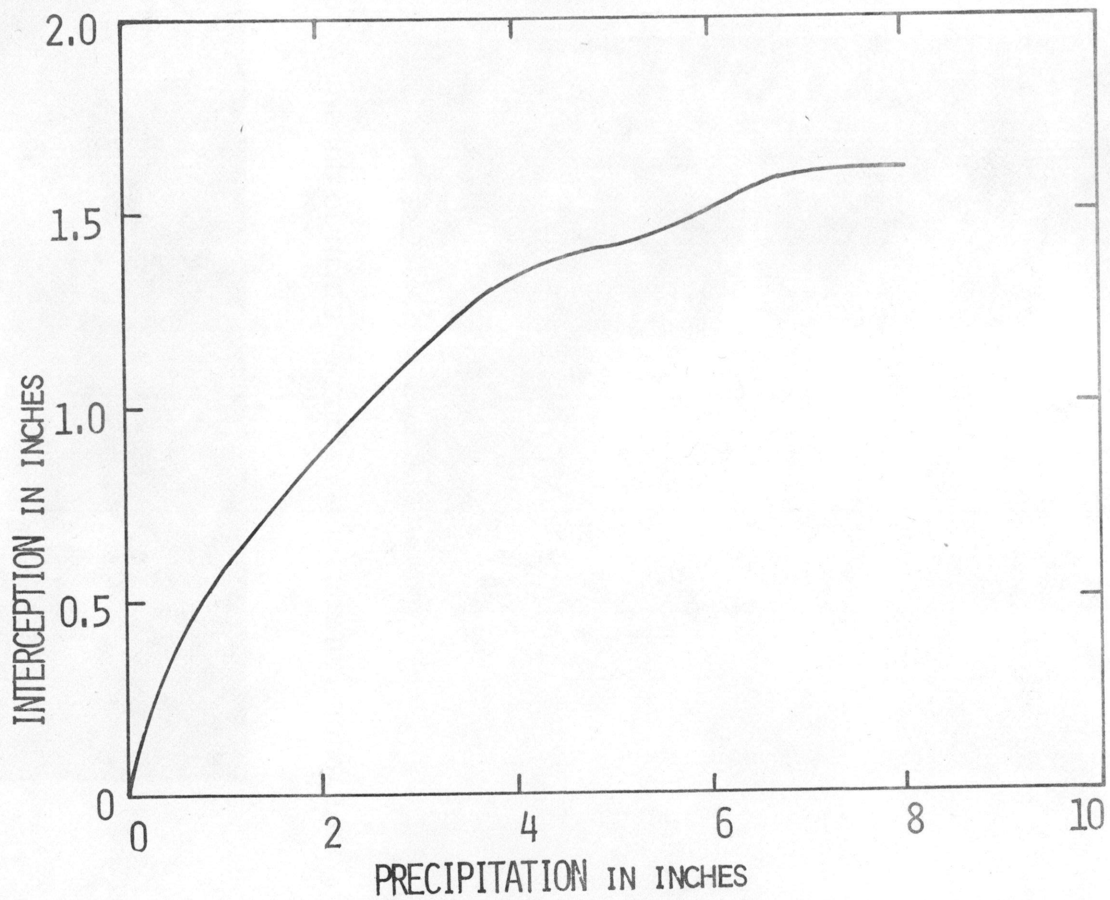


Figure 8. Interception on an artificial tree with 30 degree branch angle.

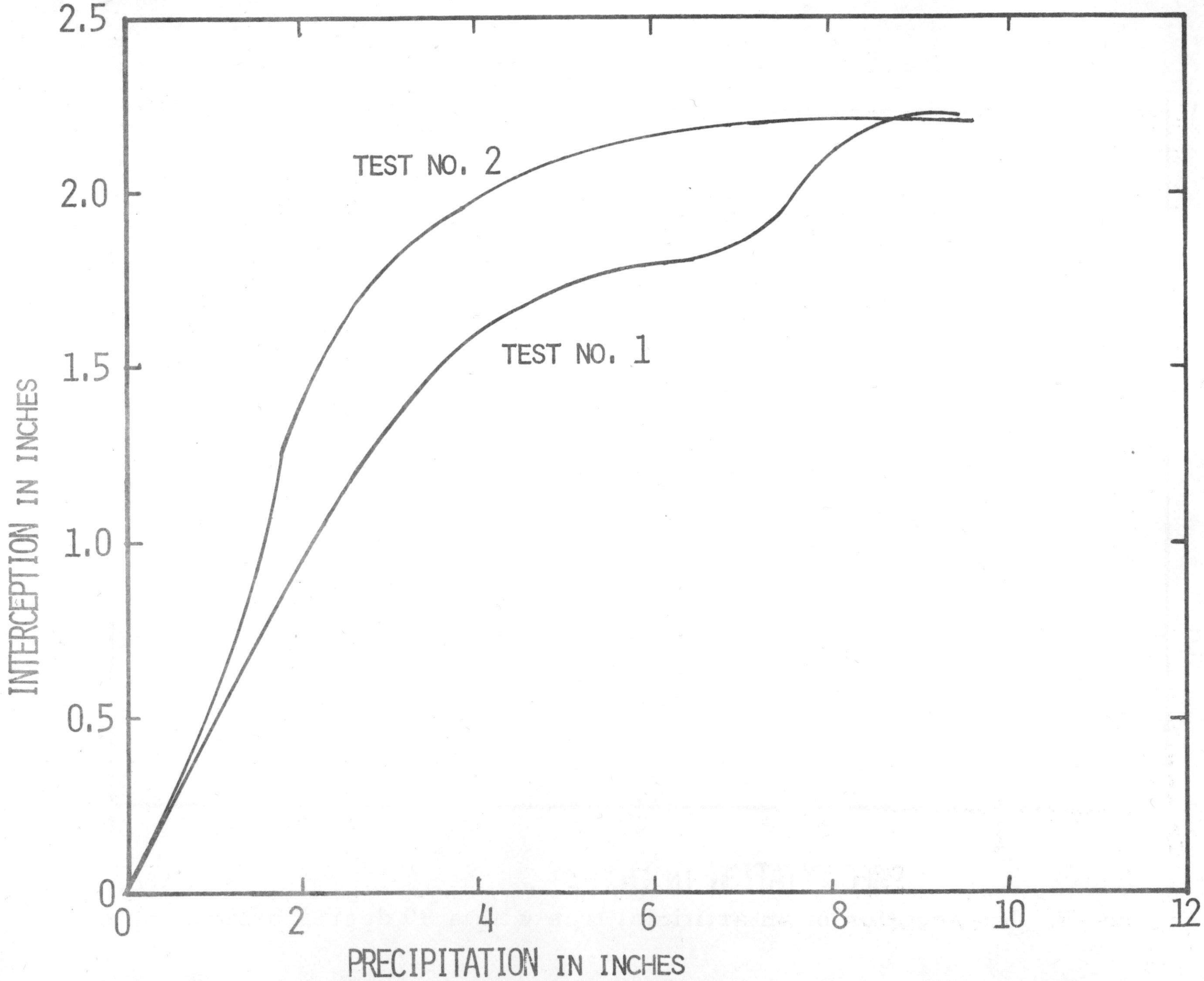


Figure 9. Test of reproducibility of interception using two 60 degree trees.

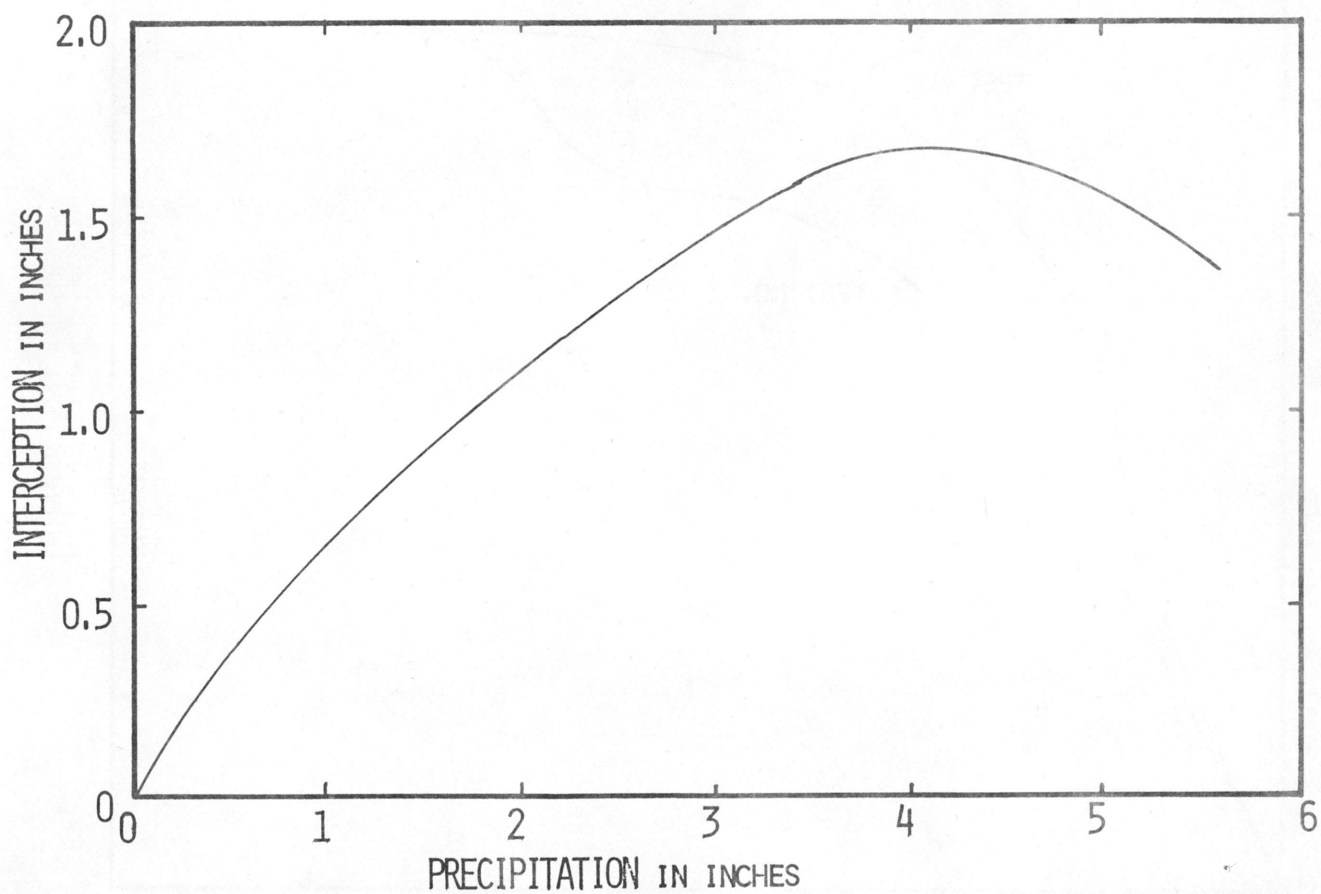


Figure 10. Interception of an artificial tree with a 90 degree branch angle.

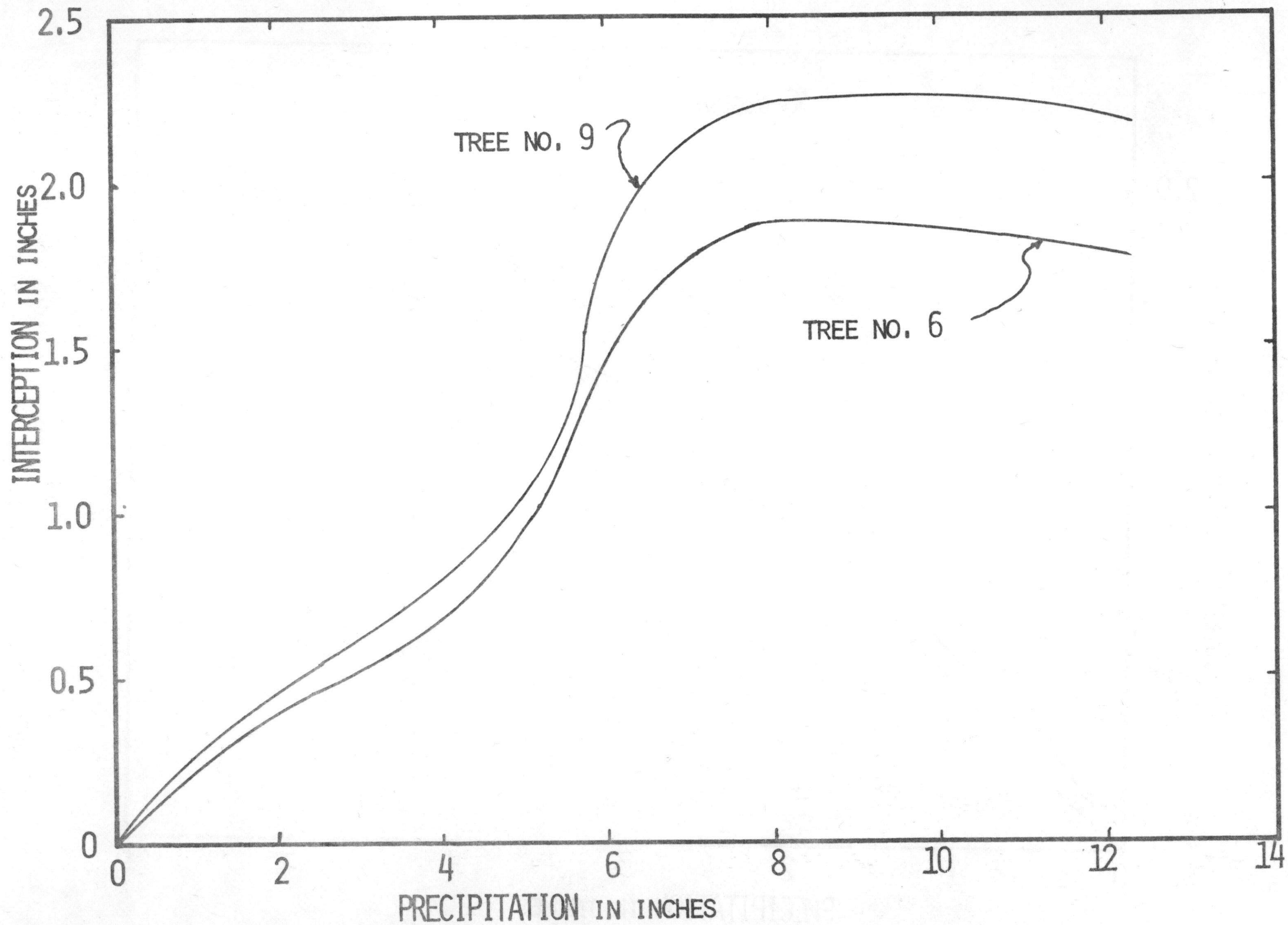


Figure 11. Interception on two similar 90 degree trees.

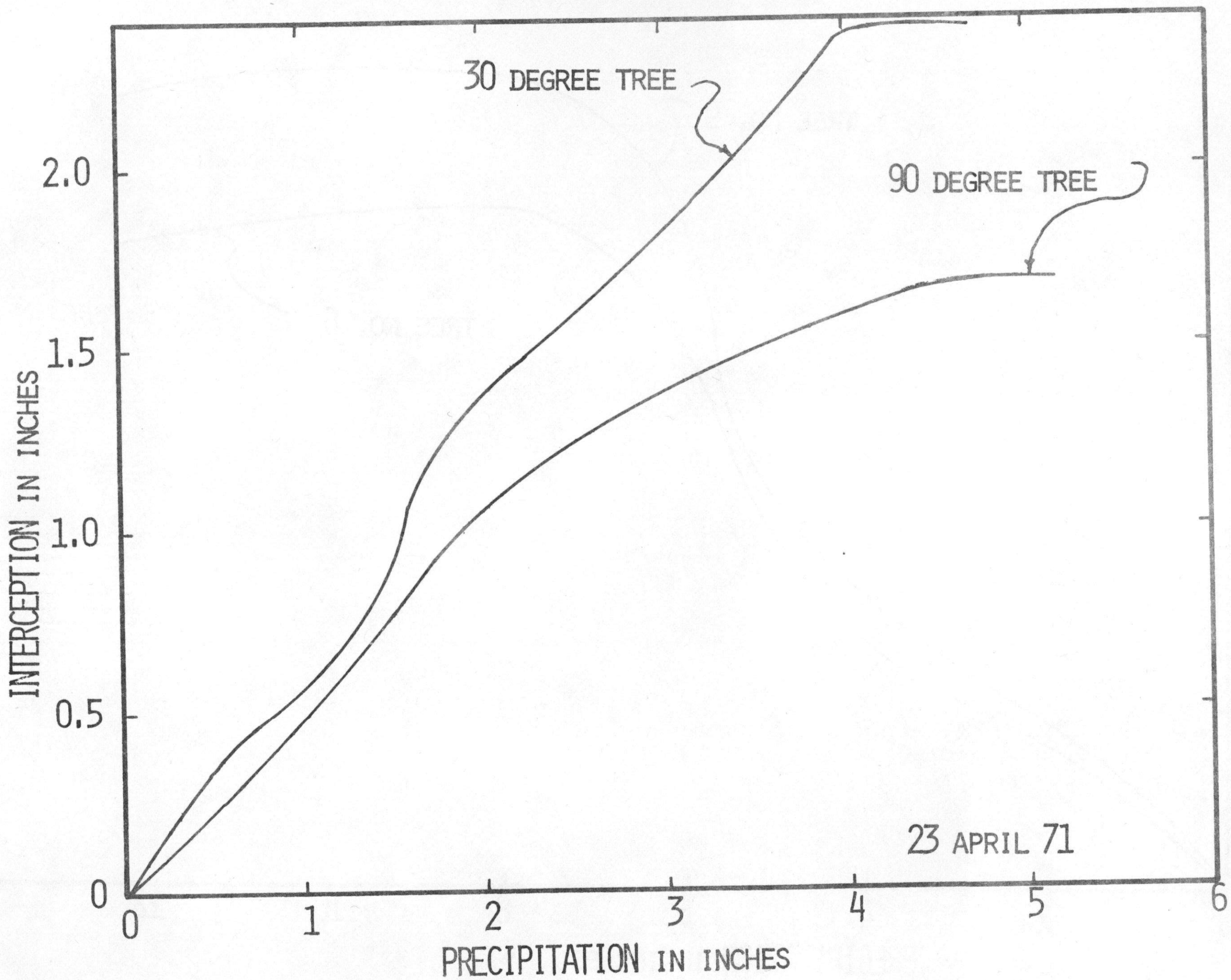


Figure 12. Comparison of interception on two trees with 30 and 90 degree angles. Test 1.

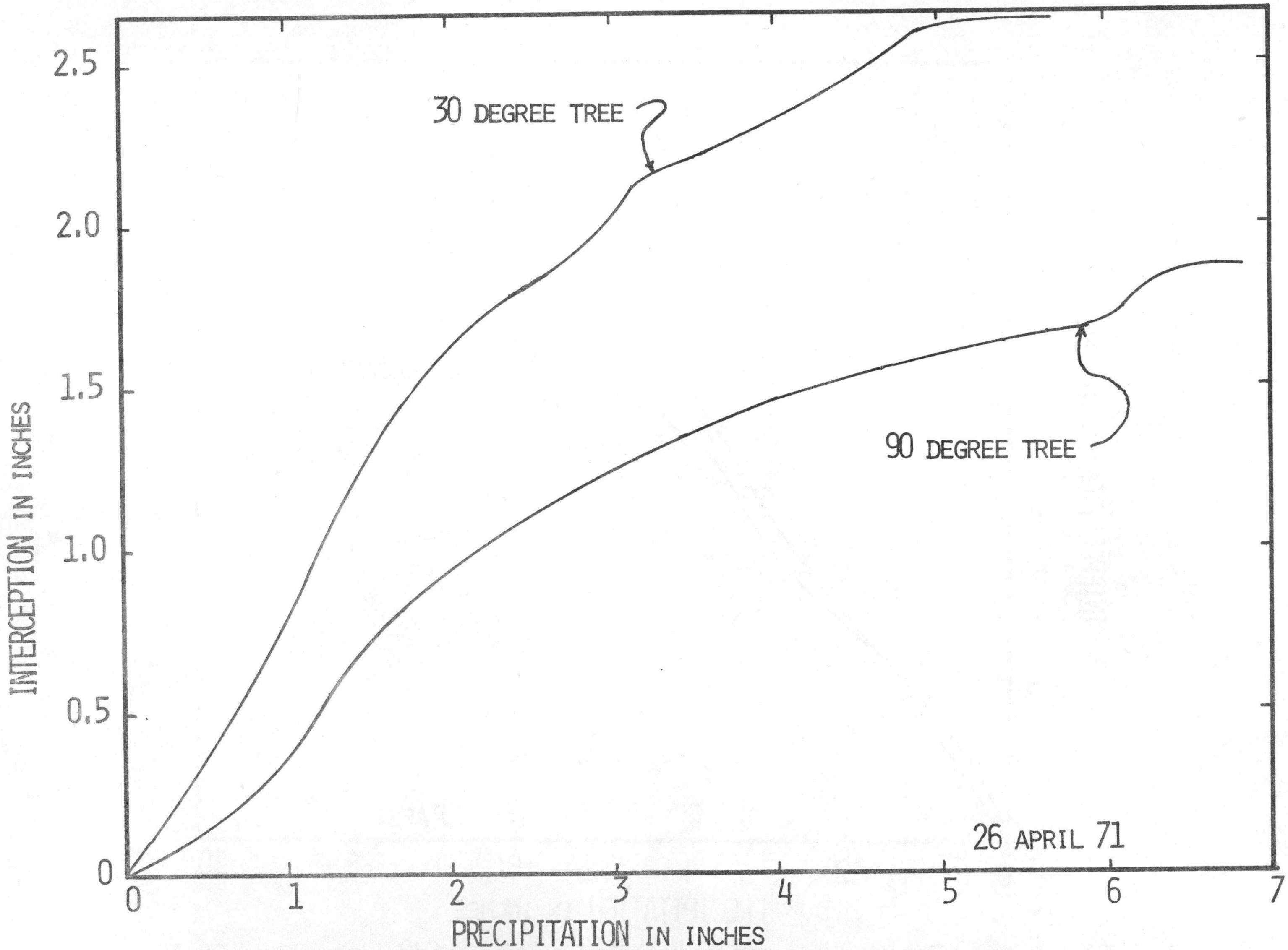


Figure 13. Comparison of interception on two trees with 30 and 90 degree branch angles. Test 2.

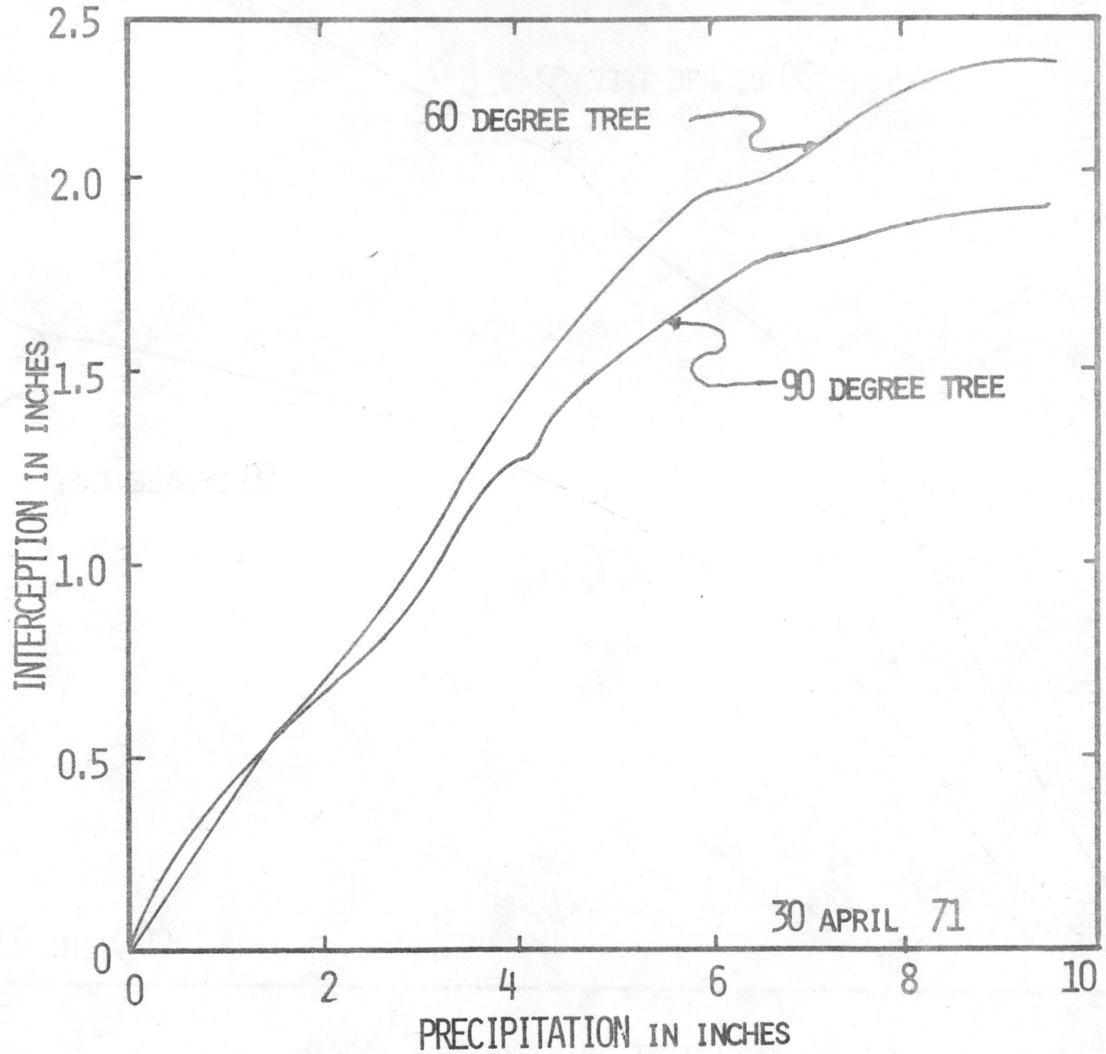


Figure 14. Comparison of interception on two trees with 60 and 90 degree branch angles.

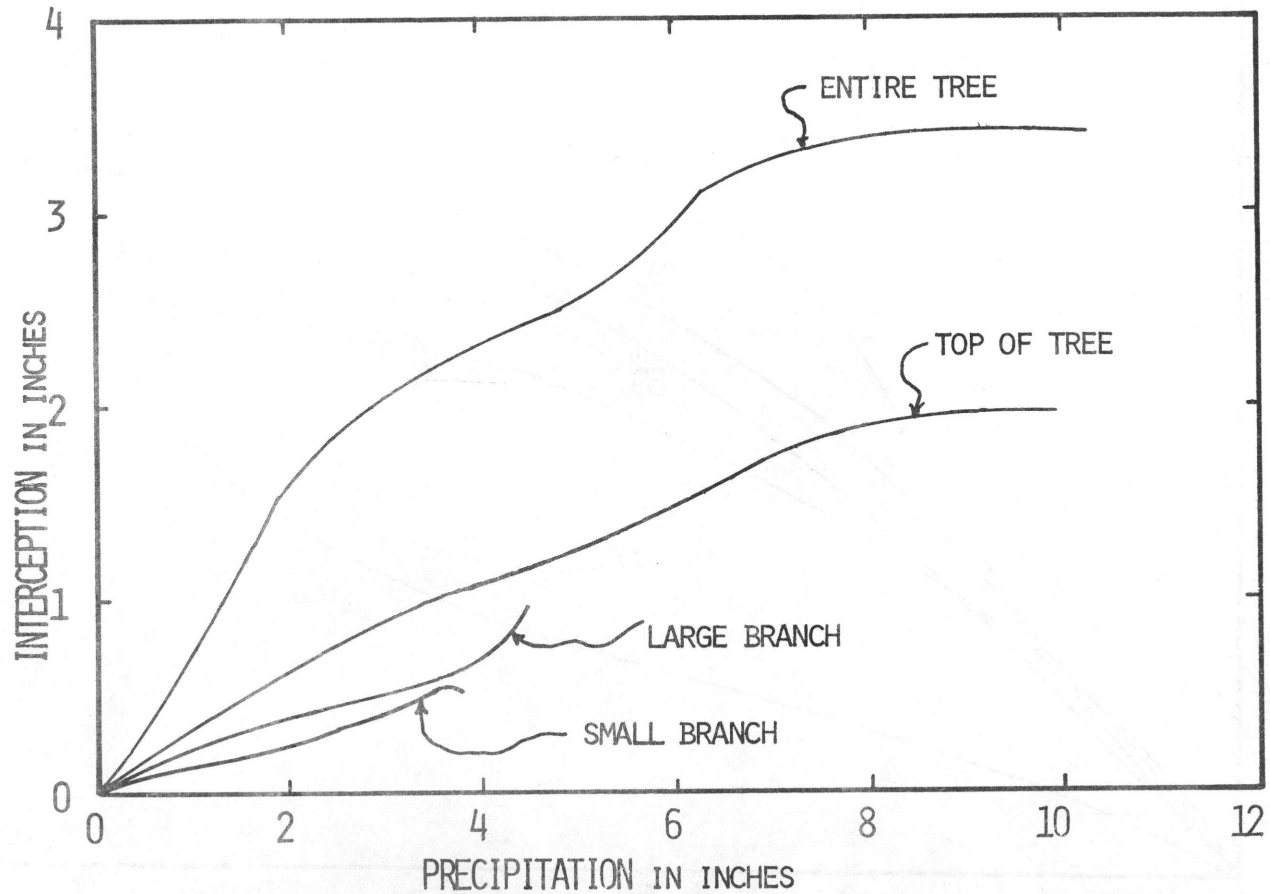


Figure 15. Interception on artificial Christmas tree (Canada Pine).

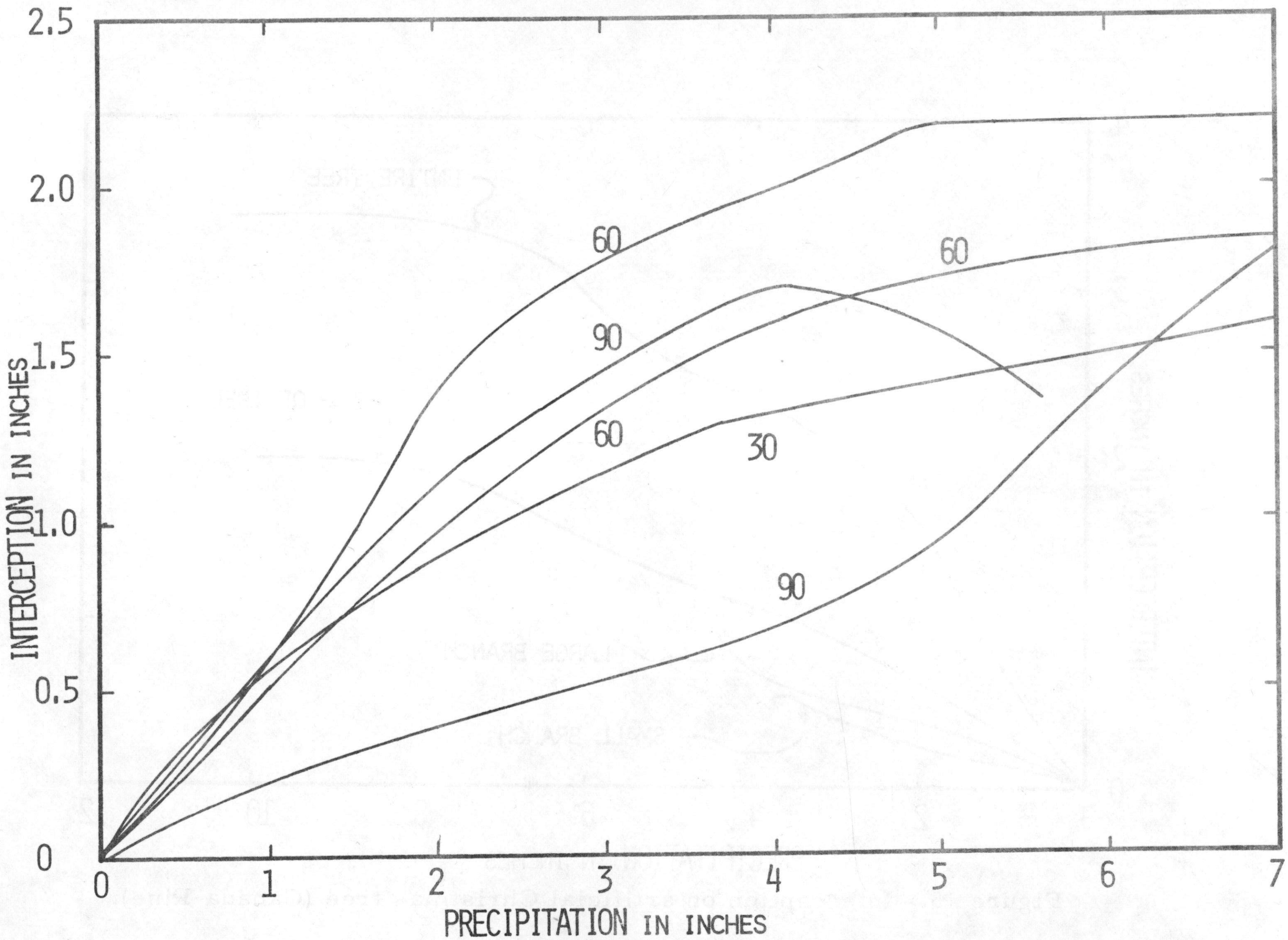


Figure 16. Composite of branch angle tests.

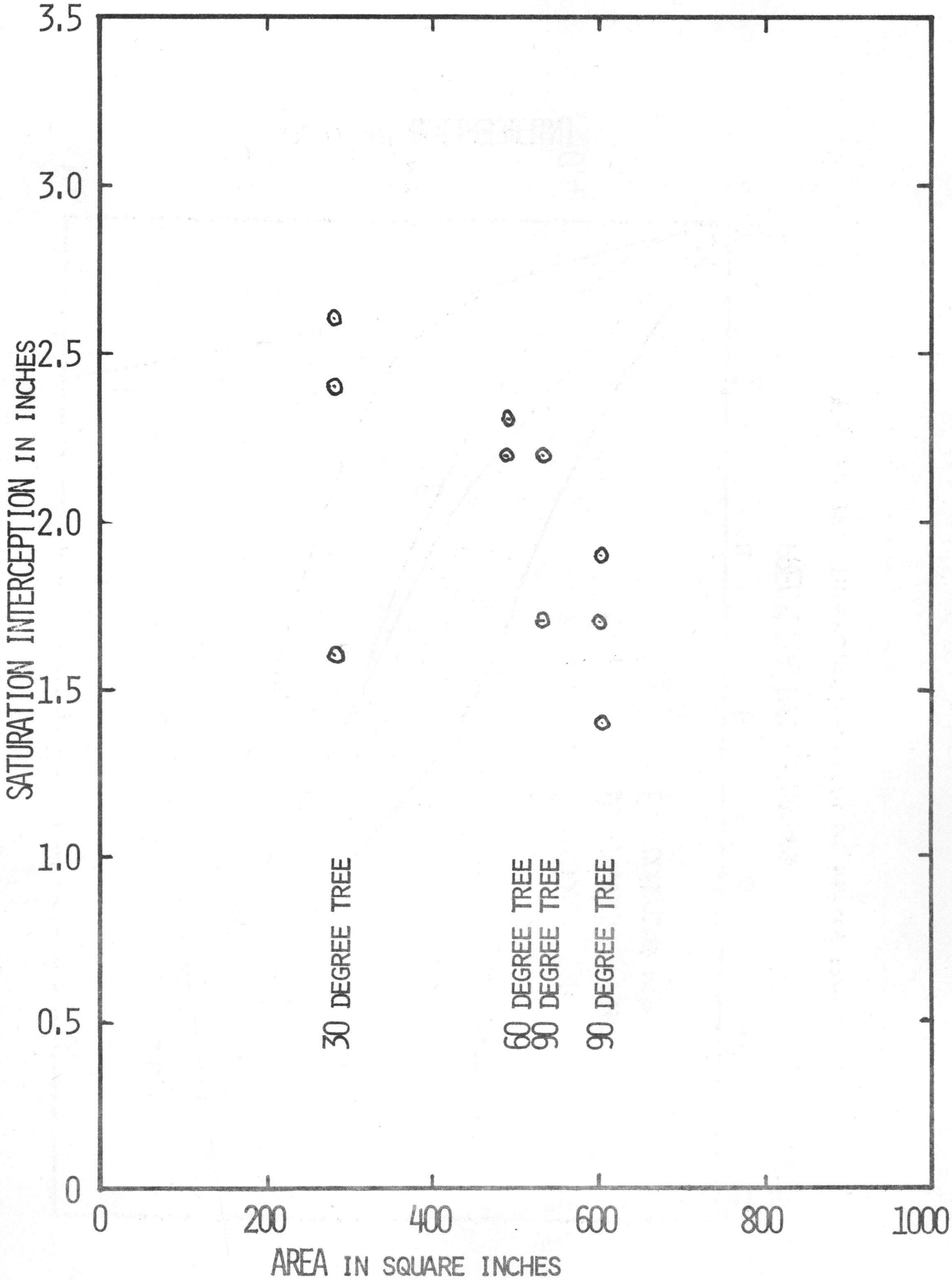


Figure 17. Effect of projected area of interception.

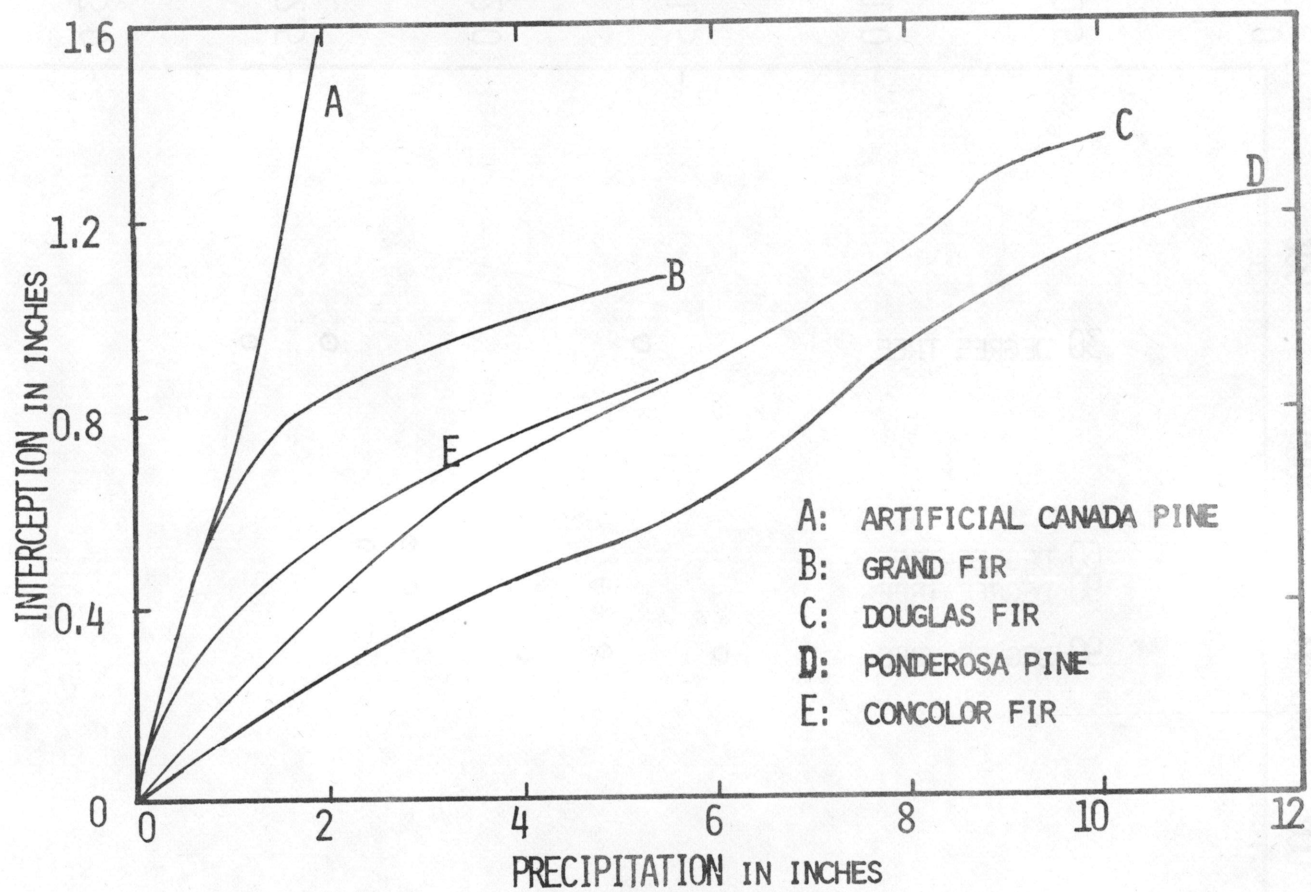


Figure 18. Interception tests on entire tree.

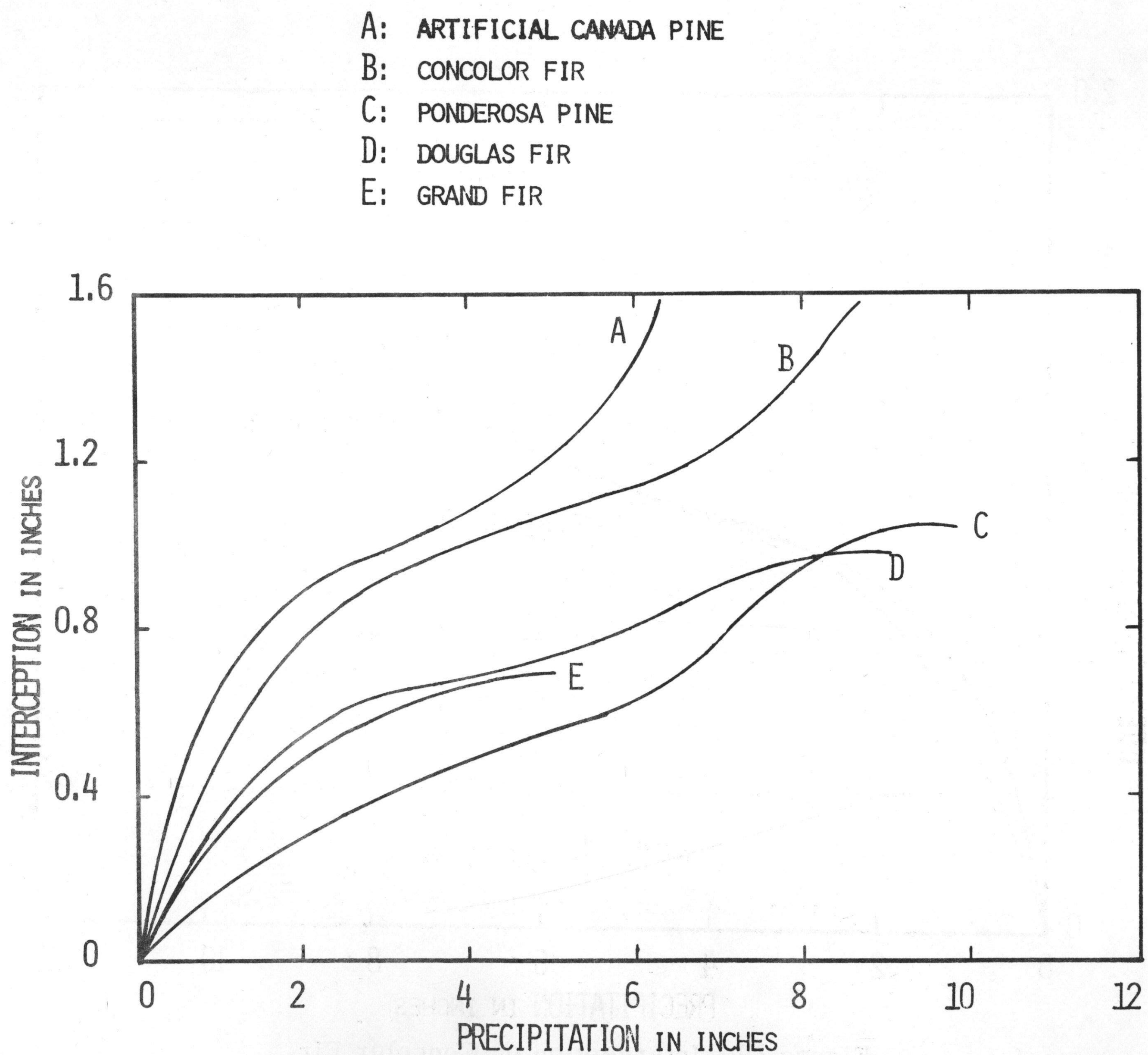


Figure 19. Interception tests using tops of trees.

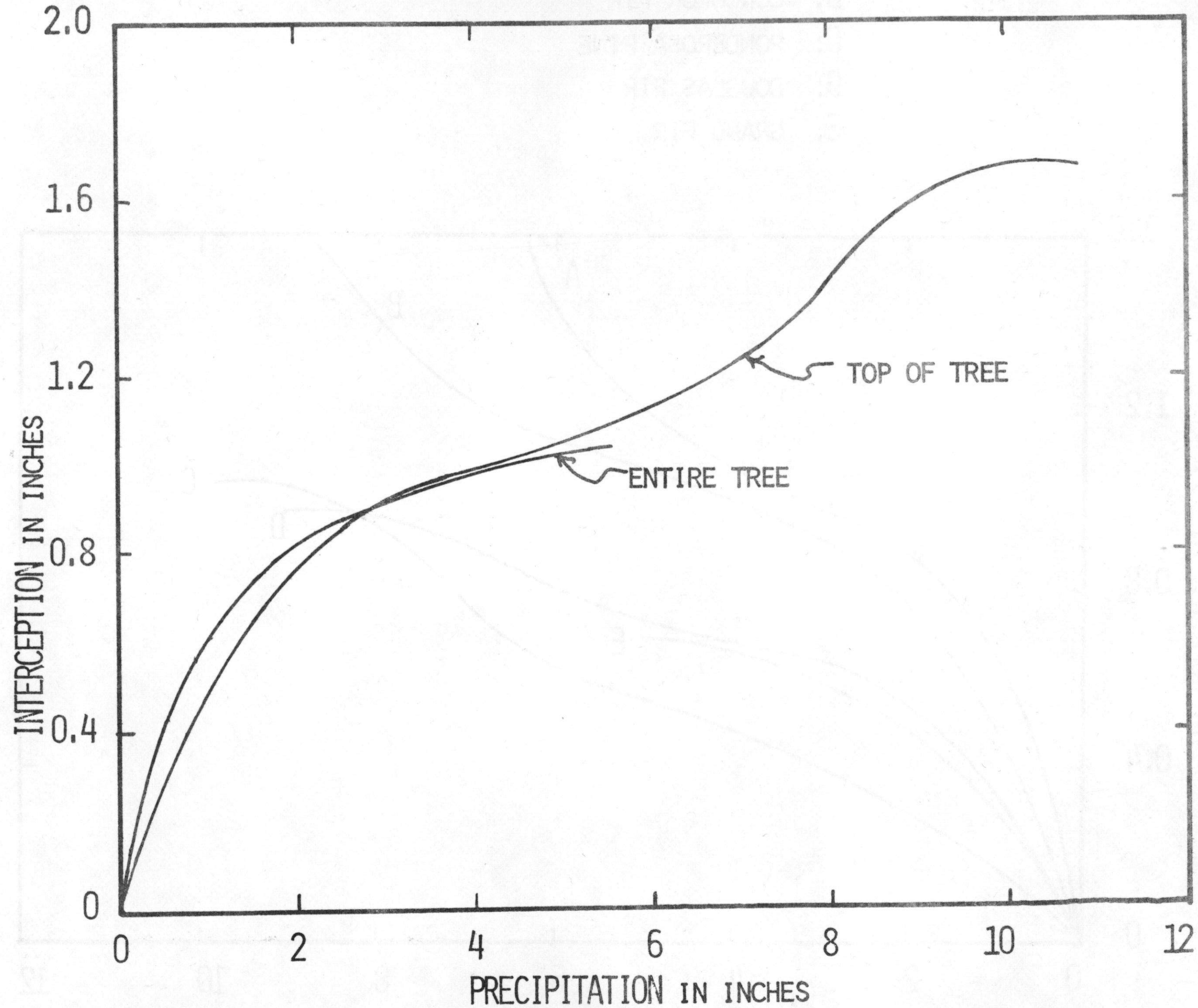


Figure 20. Interception on Concolor Fir.

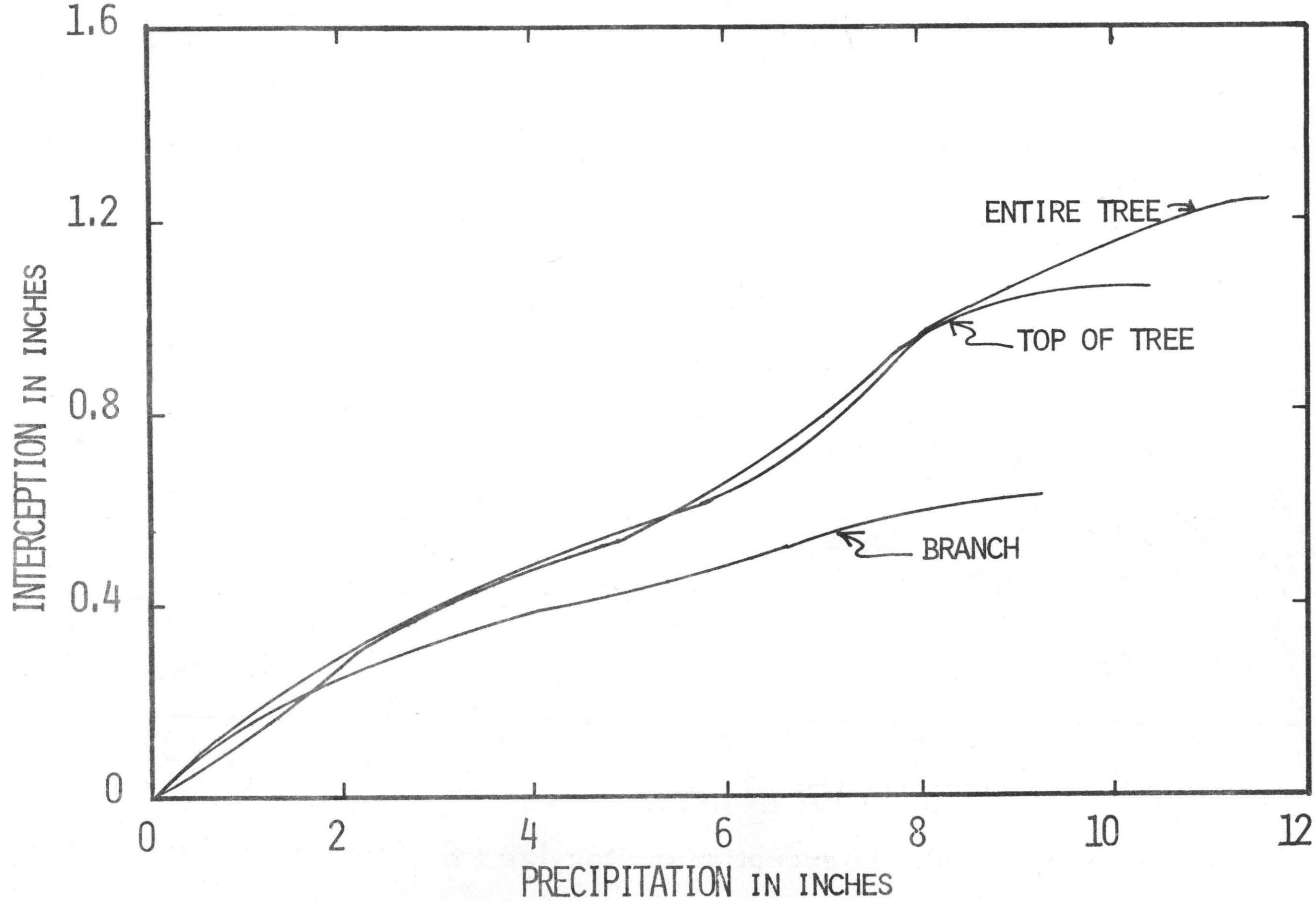


Figure 21. Interception on Ponderosa Pine.

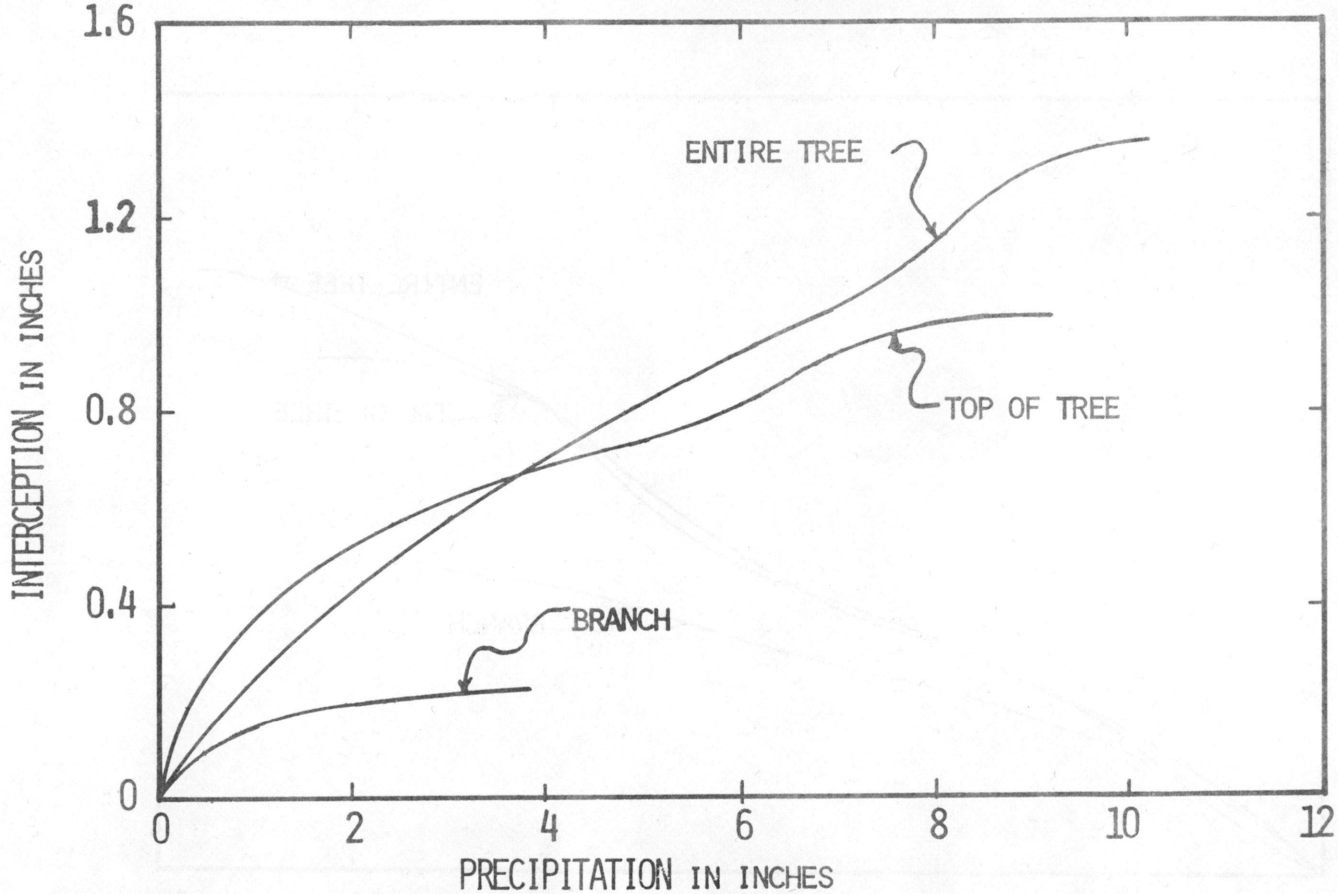


Figure 22. Interception on Douglas Fir.

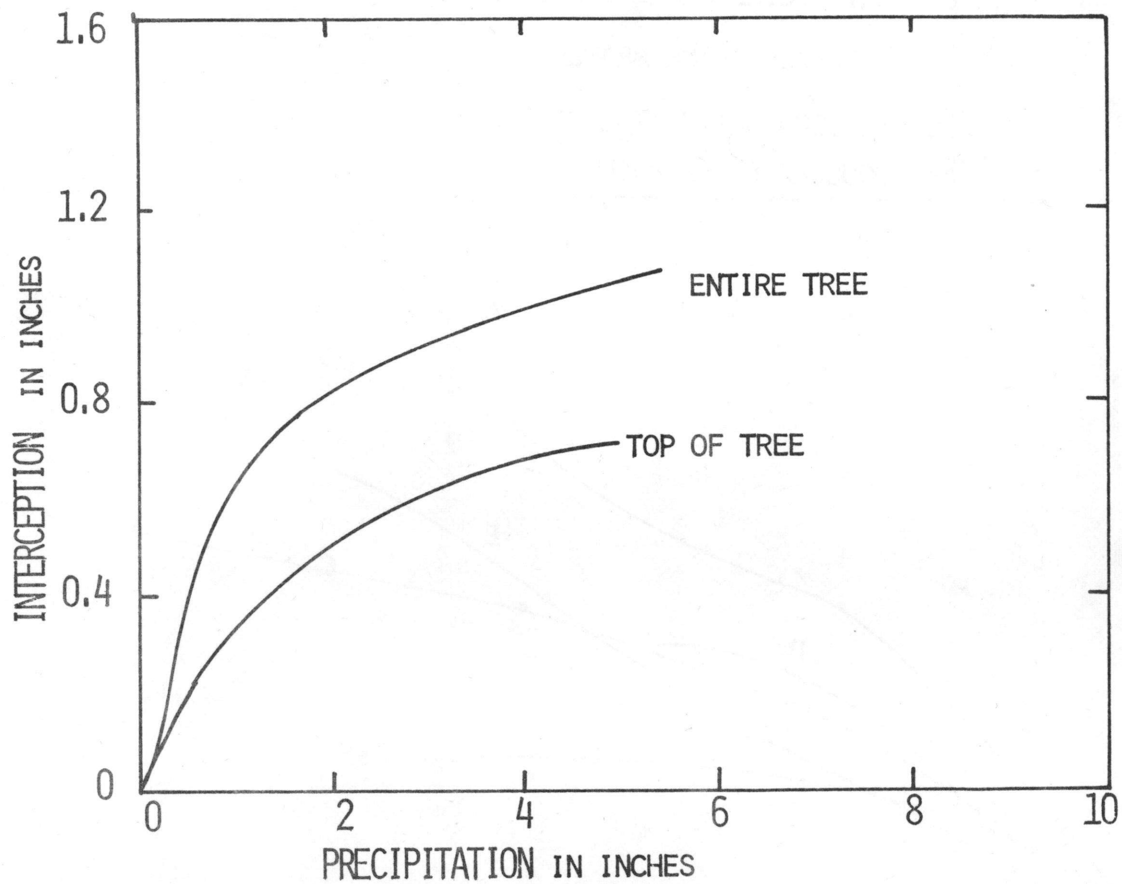


Figure 23. Interception on Grand Fir.

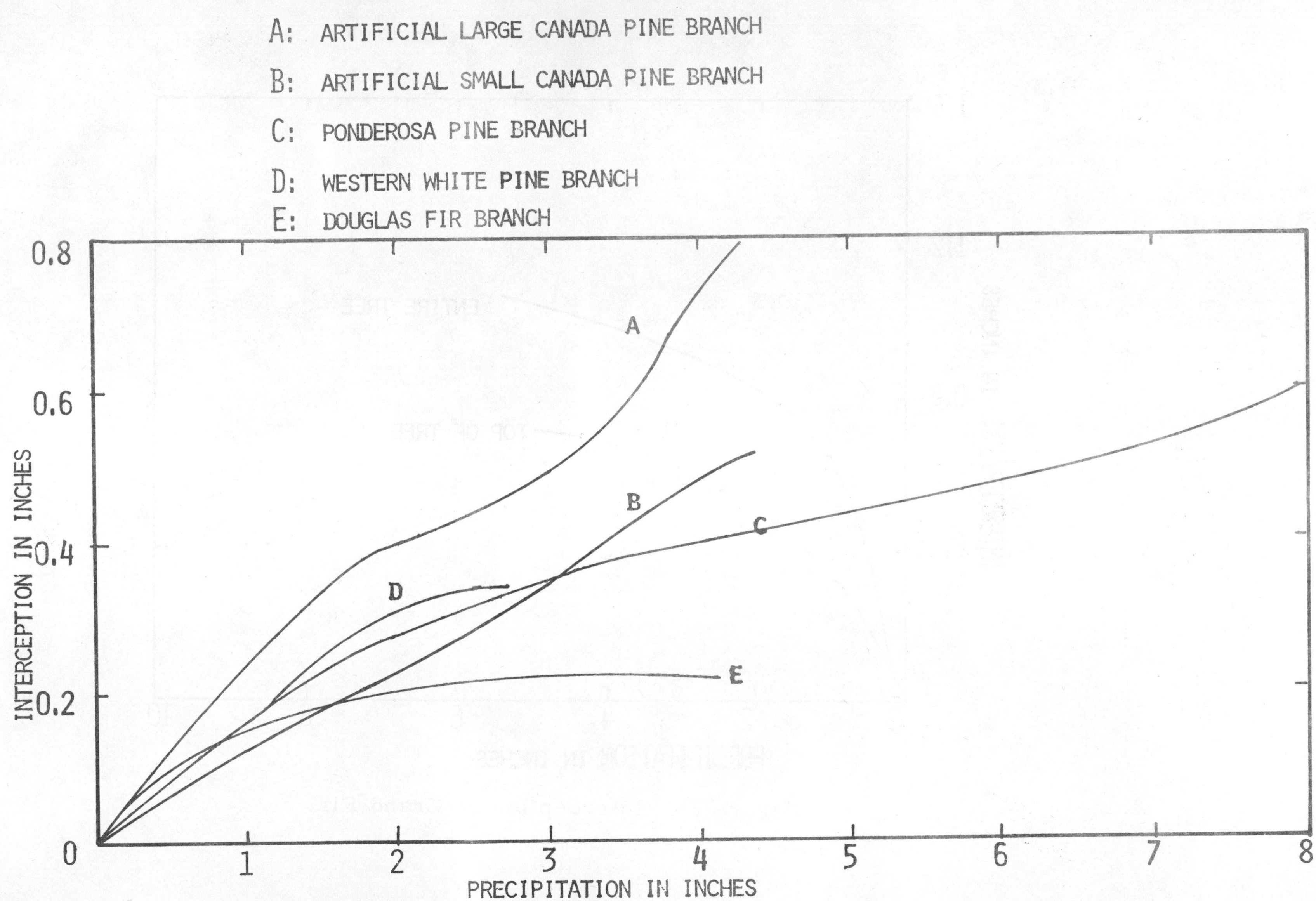


Figure 24. Interception on individual branches.